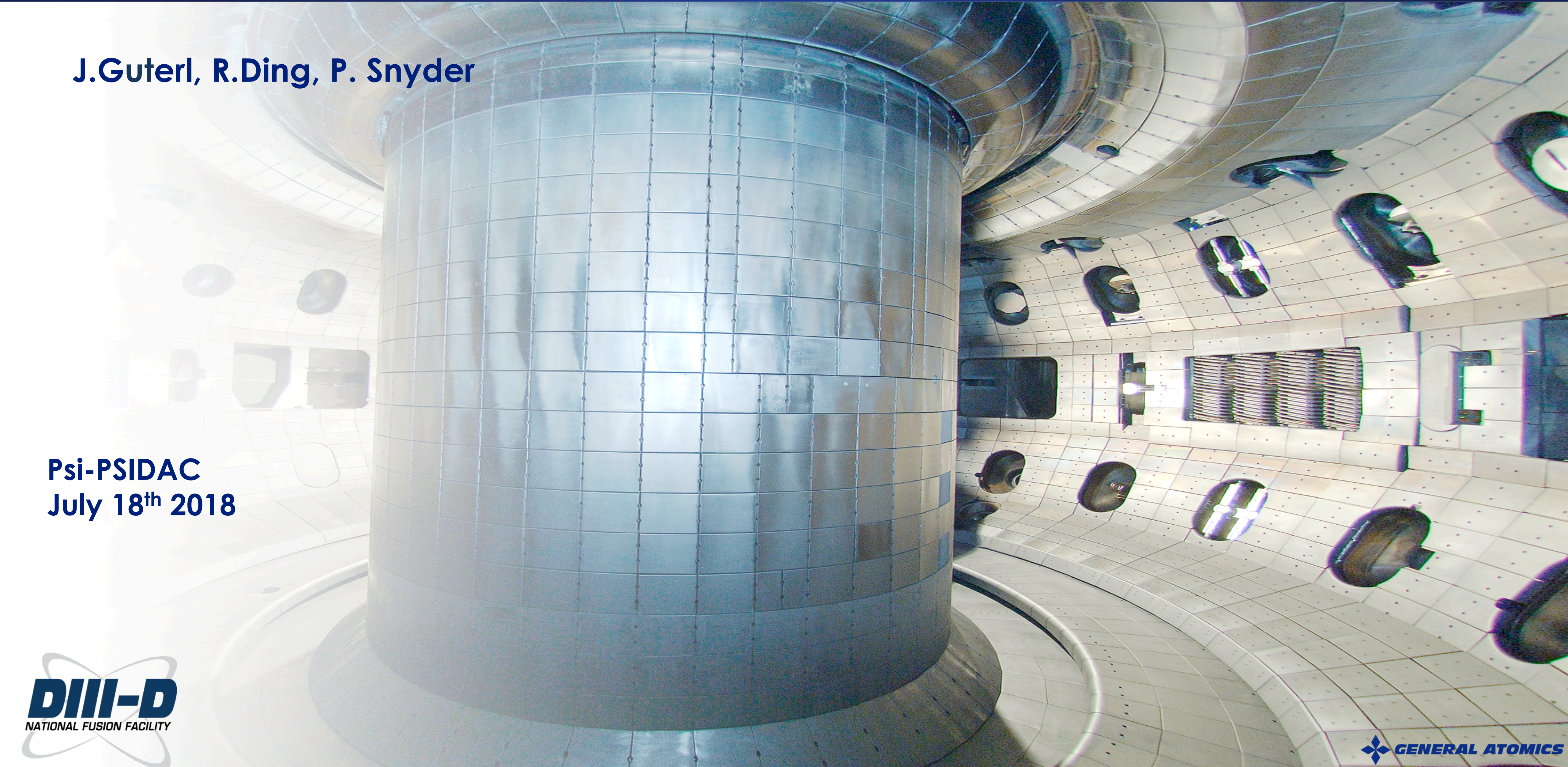
Illustrative examples of analysis and modeling of impurity erosion and redeposition experiments in DIII-D with integrated PMI models

J.Guterl, R.Ding, P. Snyder



Psi-PSIDAC
July 18th 2018

DIII-D
NATIONAL FUSION FACILITY

GENERAL ATOMICS

Outline

- Modeling of W ring experiments in DIII-D:
  - C and W erosion/redeposition in DIII-D divertor can be consistently modeled using a Monte-Carlo impurity transport code and sheath & material reduced models*:
    - → *Experimental and theoretical framework in DIII-D to validate and use impurity transport code in Tokamak conditions (GITR)*
  - Accurate modeling of C deposition on W may however require a more detailed material model:
    - → *Experimental framework in DIII-D to validate integrated models of surface evolution and roughness, material erosion and impurity transport*
- Modeling W redeposition with ion-gyro sheath:
  - reduced model vs PIC model?
    - → *Example of experimental framework in DIII-D to benchmark PIC simulations with ITER relevant physics*

* Presented at the 23rd international conference on Plasma Surface Interactions in Controlled Fusion Devices

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  - Why modeling W net erosion is challenging?
  - Measurement of W gross erosion and outboard deposition in DIII-D lower divertor with a toroidally symmetric W source

– Modeling and analysis of W gross erosion mechanism
  - W sputtering results from synergetic effects between impurity erosion, implantation, redeposition and transport processes

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WI (400.9 nm) +SXB

[AbramsNF2016,DingNF2017,HakolaPS2016]

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Post-mortem analysis of W deposition on PFCs

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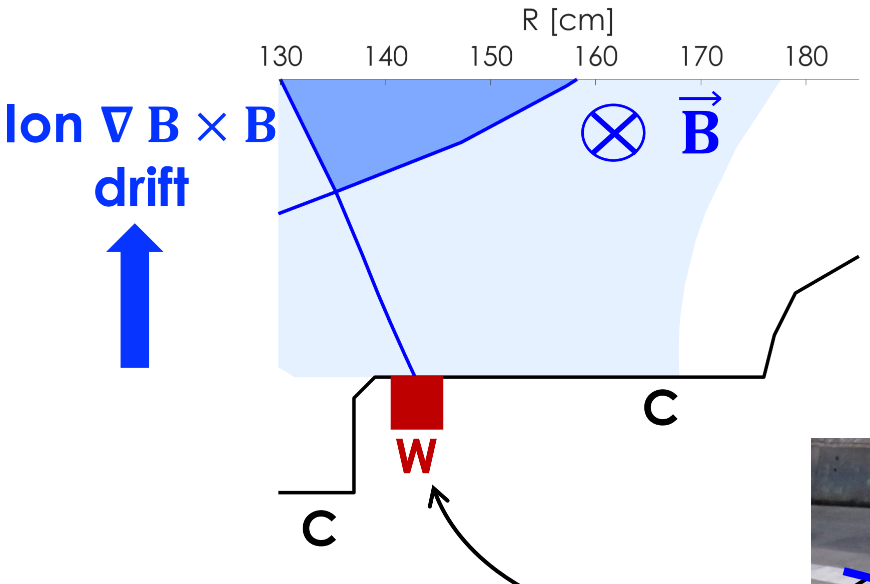
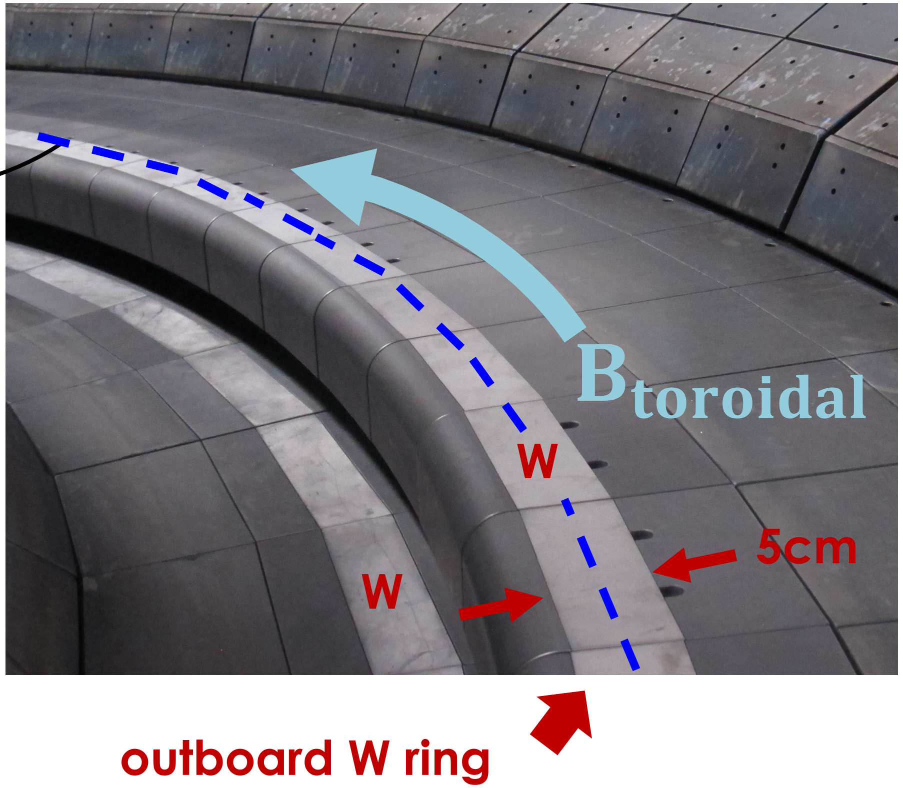
Can dedicated experiments with **localized toroidally symmetric W source** in divertor improve understanding of mechanisms governing W net erosion and transport?

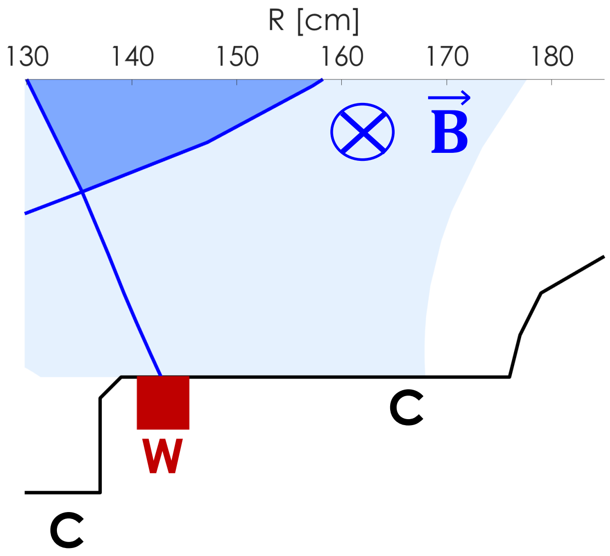
W metal ring experiments in DIII-D: introducing a localized and toroidally symmetric W source in the DIII-D lower divertor



- W rings in DIII-D lower outer divertor:
  - **localized** and **toroidally symmetric** W source
- 25 repeated attached L-mode shots in **reverse Bt-field** with outer strike point on the outboard W ring



Γ_W^{ero}~0.1% Γ_D on W ring and net deposition of C on W near the separatrix



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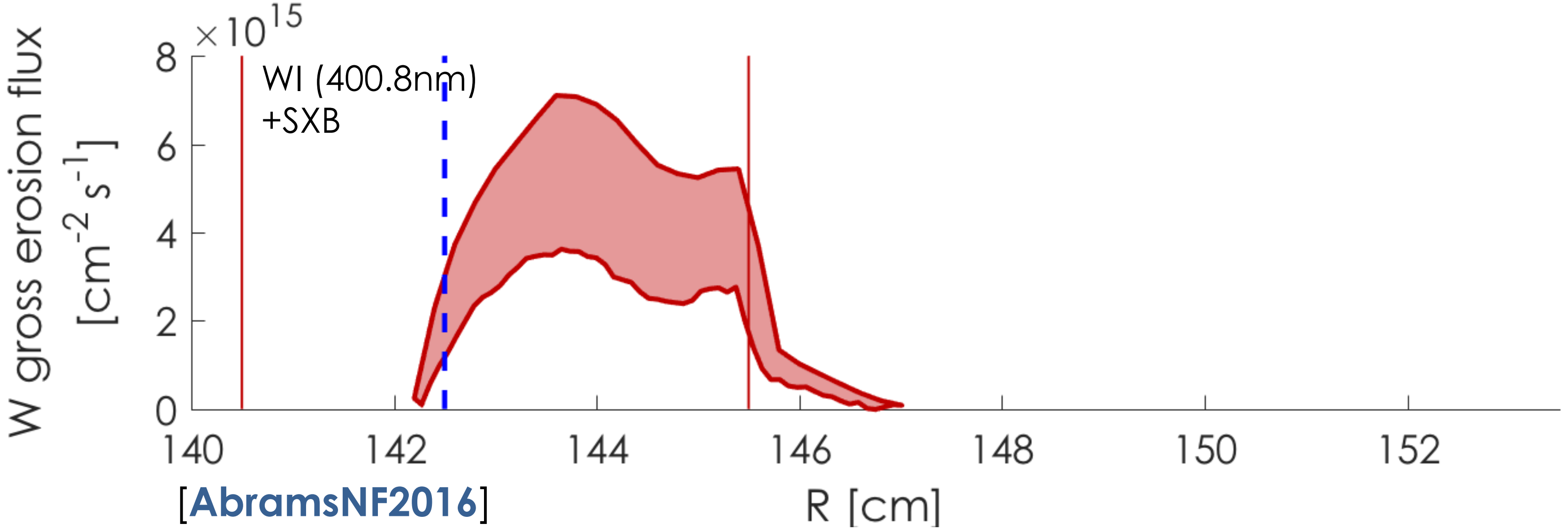
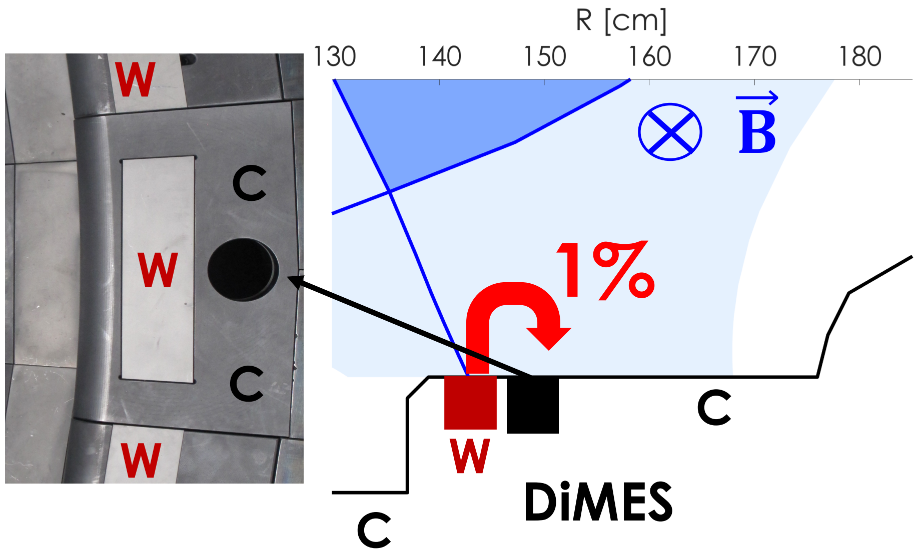


[AbramsNF2016]

Outboard W deposition ~1% Γ_W^{ero} measured at 3.5cm from W outer edge



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- Inter-shots measurements of W outboard deposition
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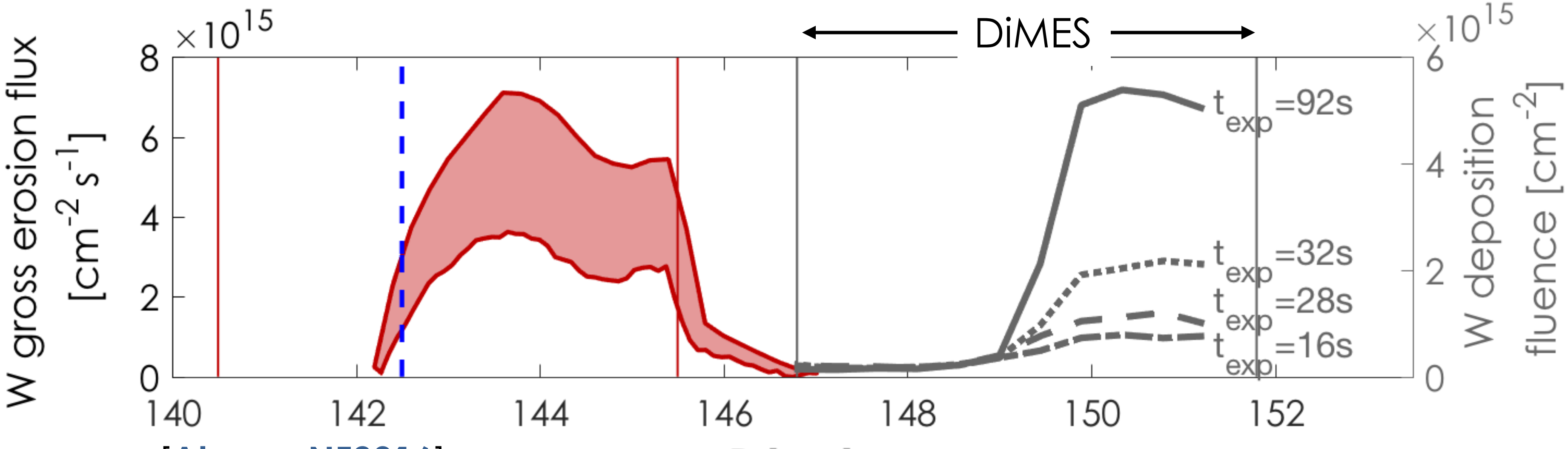
[WamplerPS2017]



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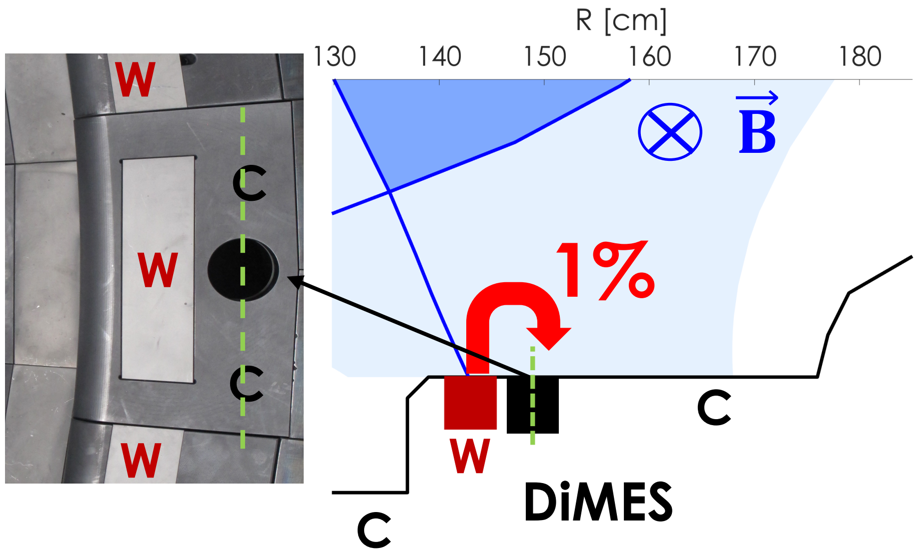

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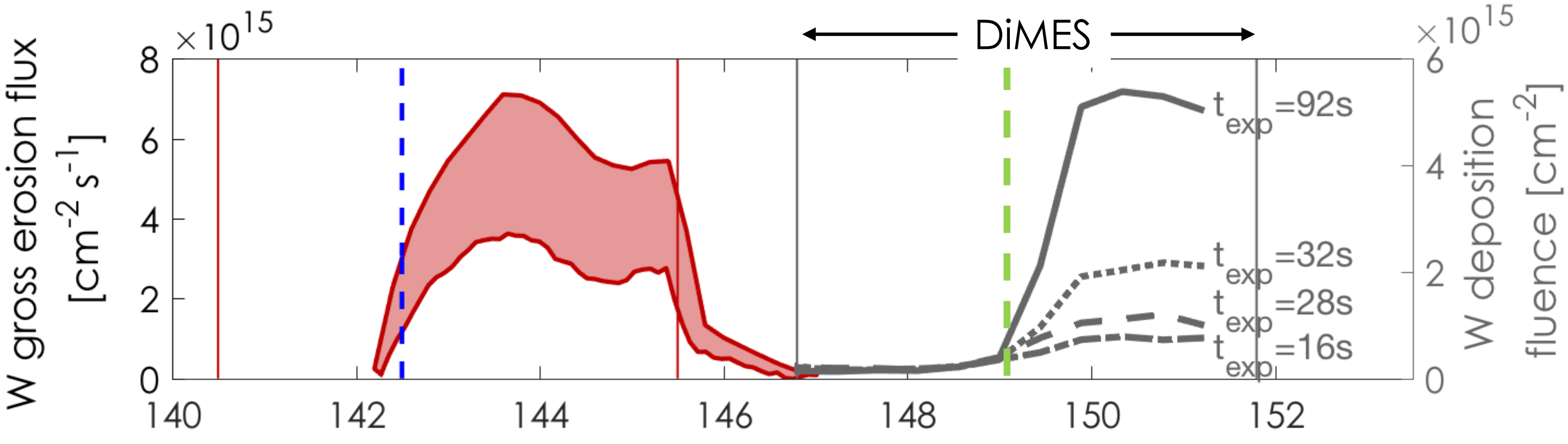
  - **very localized W deposition at 3.5cm from W outer edge**



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- Modeling of W + C local erosion, redeposition and transport with ERO-D3D (~ERO [KirschnerNF2000]):
    - Fully parallelized Monte-Carlo solver (trace approximation)
    - 3D + ion gyro-sheath + collisions with D + ExB & $\nabla B \times B$ drifts
    - C+W homogenous mixed-material model [KriegerJNM1993]
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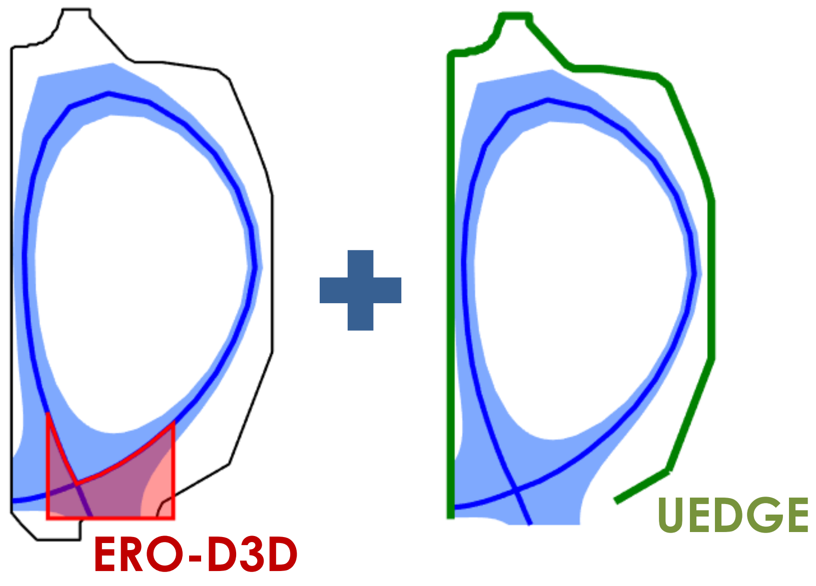

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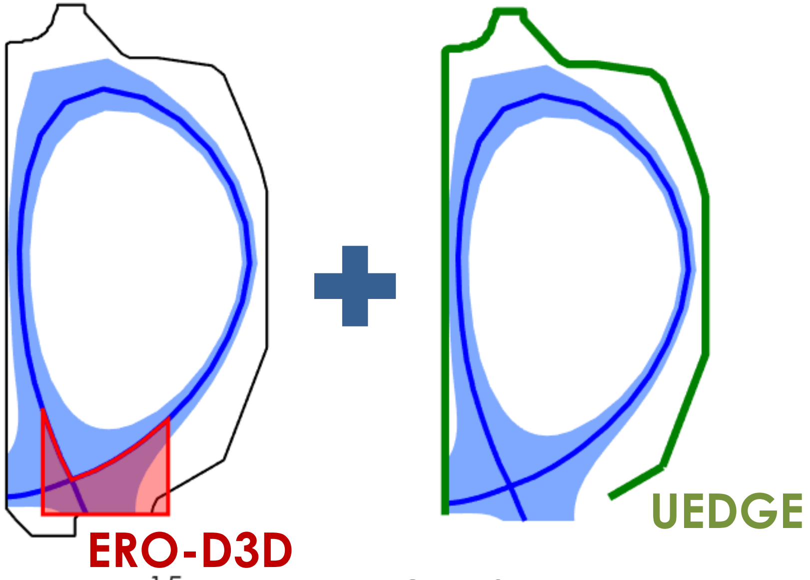

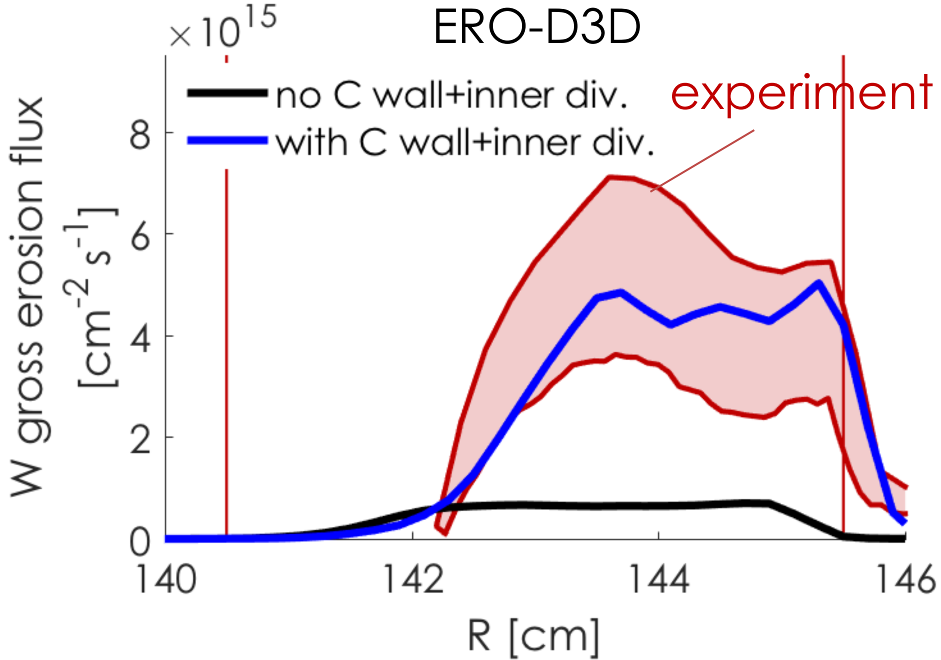

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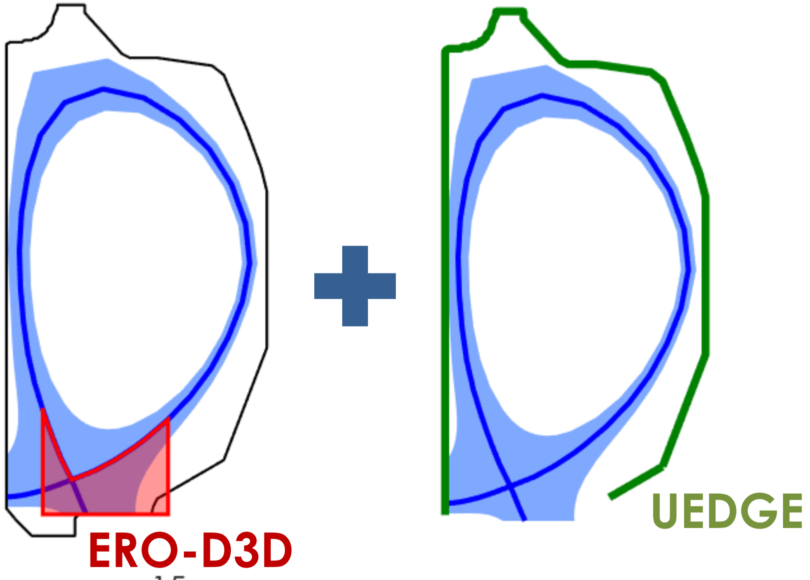
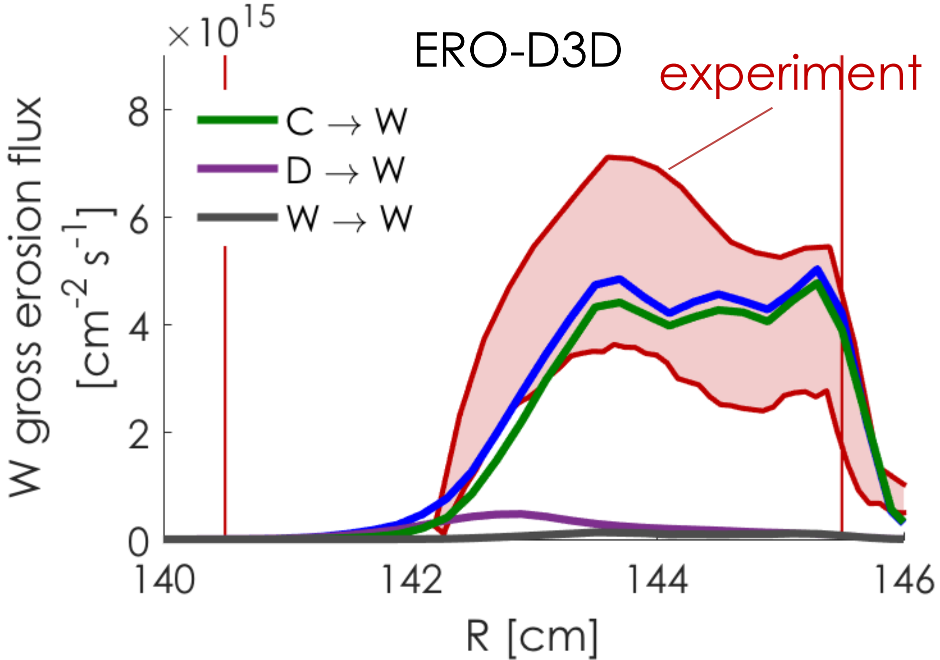
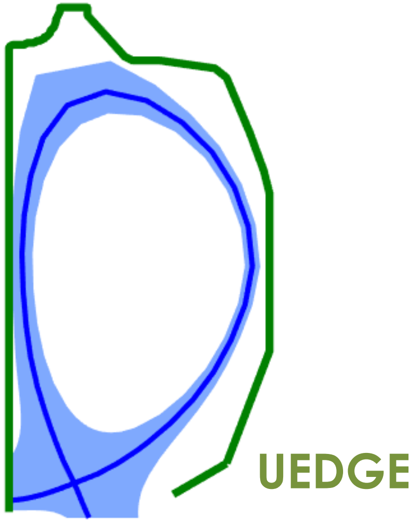
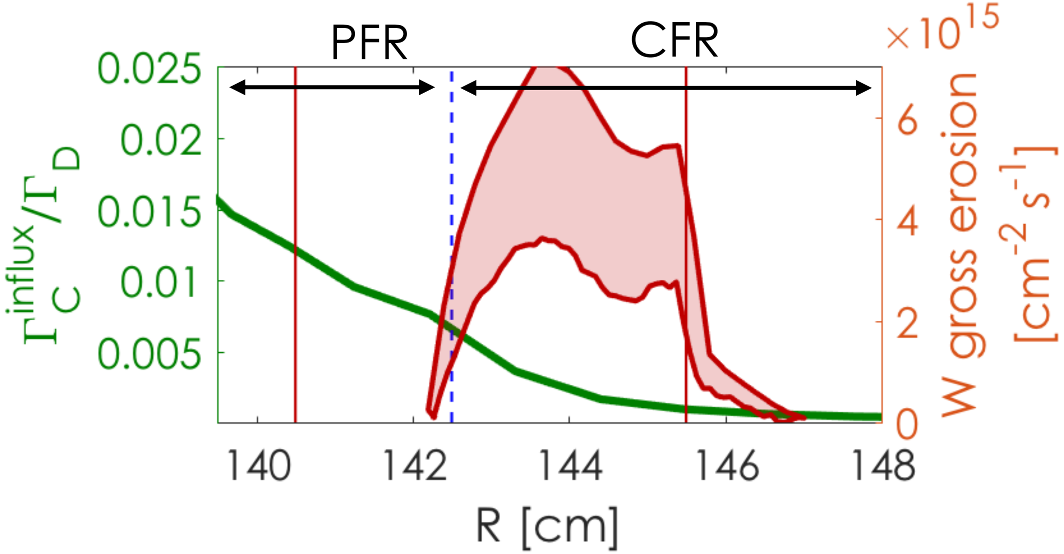




Influx of C from inner divertor and main chamber wall on W is localized near the separatrix



C influx at the outer divertor target without C source from outer divertor



- Small C influx on W in the common flux region (CFR): ~0.1% Γ_D
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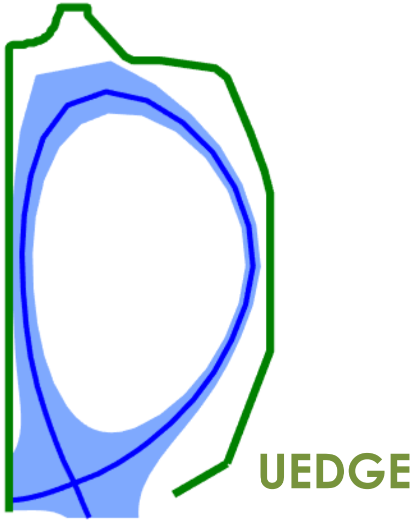

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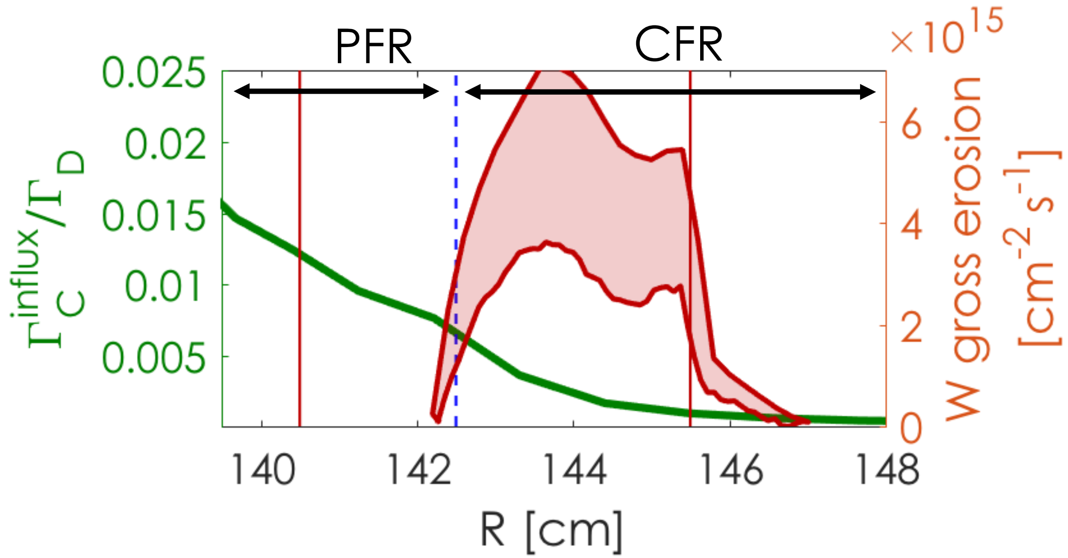

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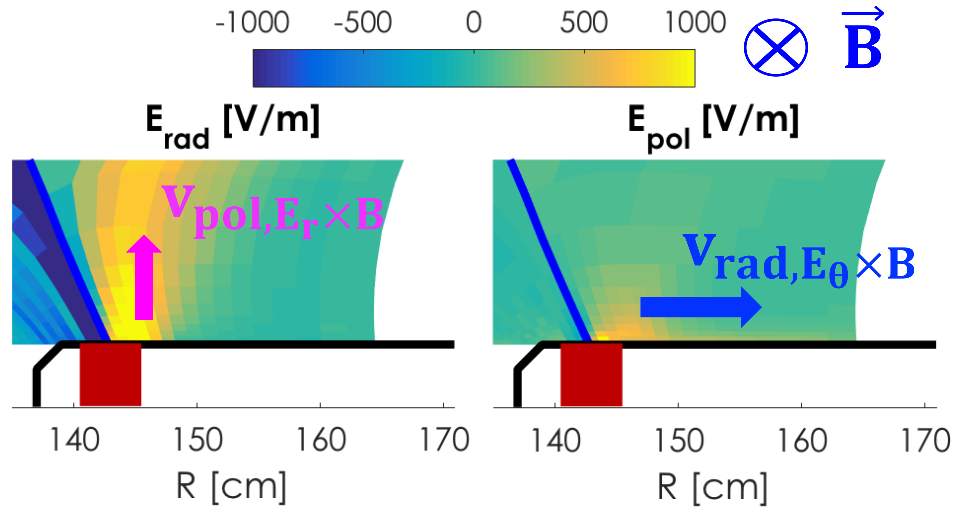
- **W gross erosion mainly occurs in the common flux region: how C migrate on W from the separatrix into the common flux region?**

Outward radial migration of C above W due to interplay between radial and poloidal ExB drifts



- Downward poloidal ExB drift in PFR/Upward poloidal ExB drift in the CFR
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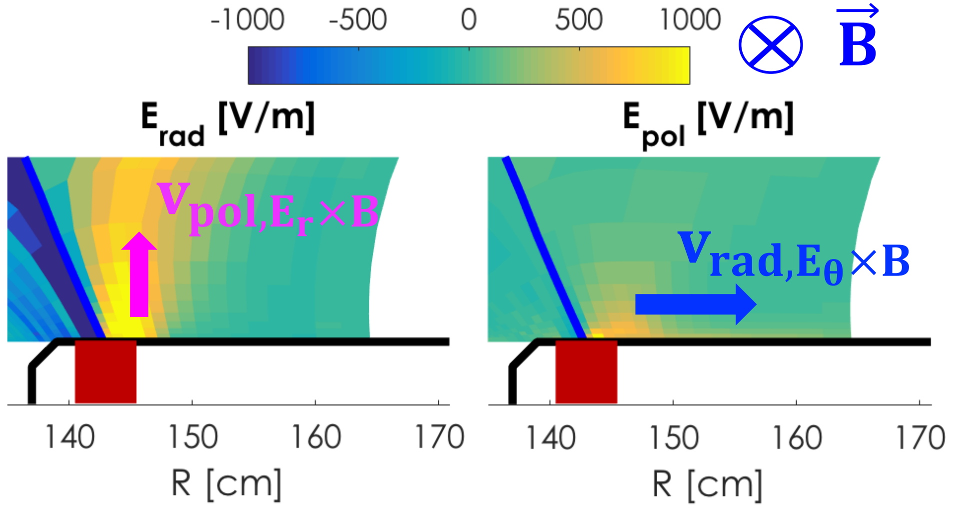

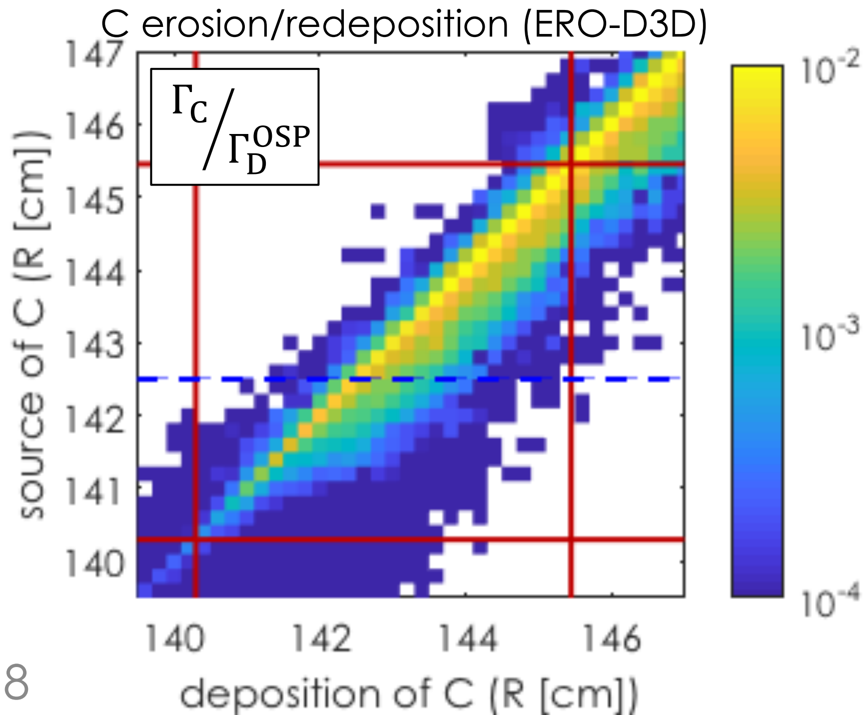

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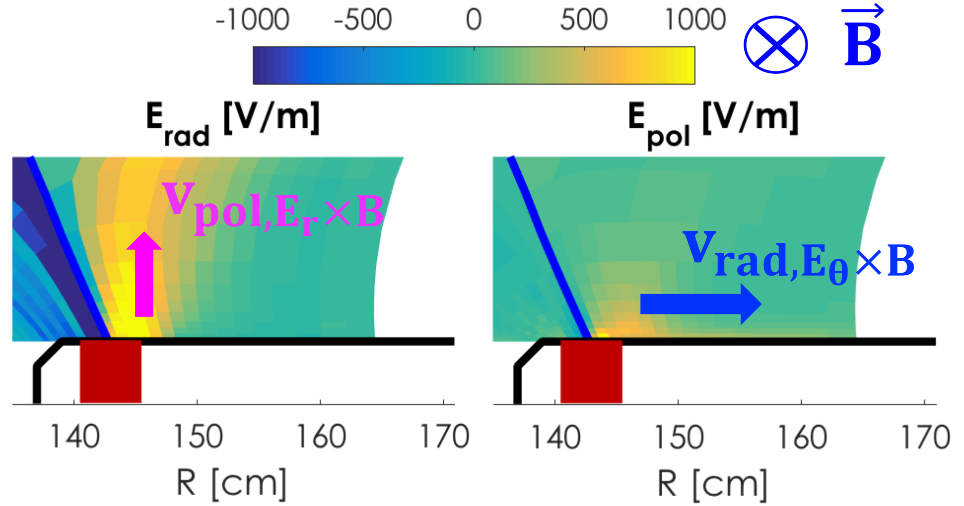

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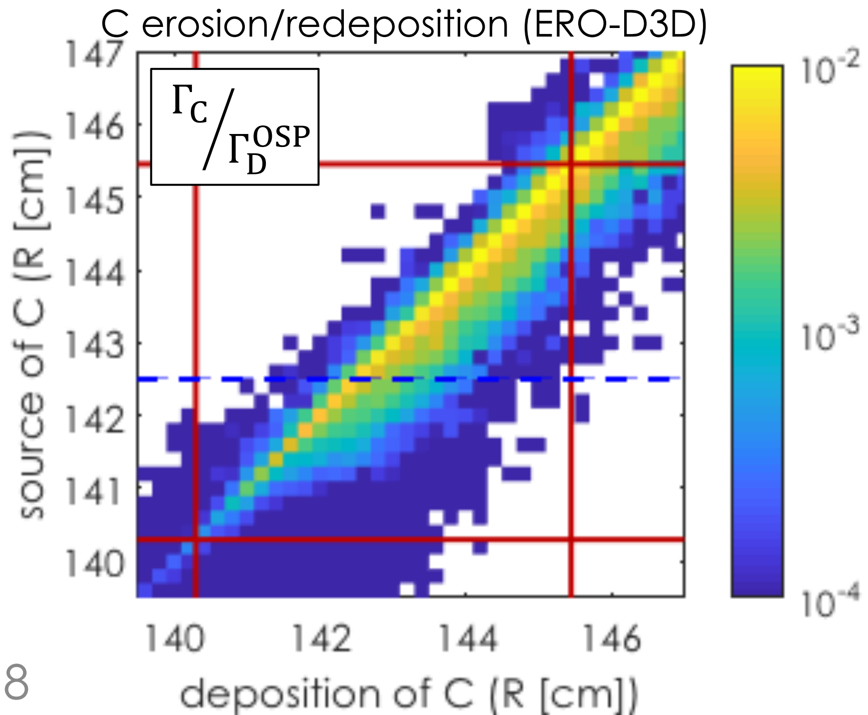
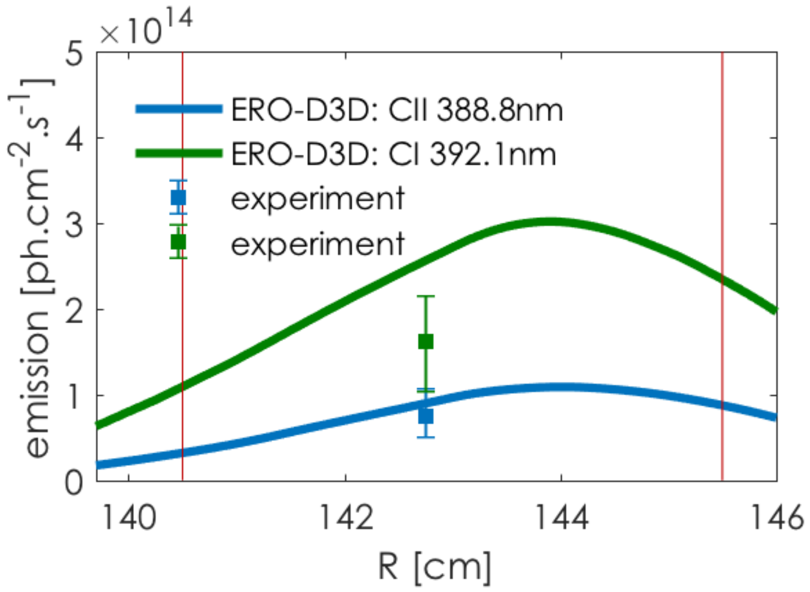


- **C content above W predicted with ERO-D3D in agreement with experimental observations**



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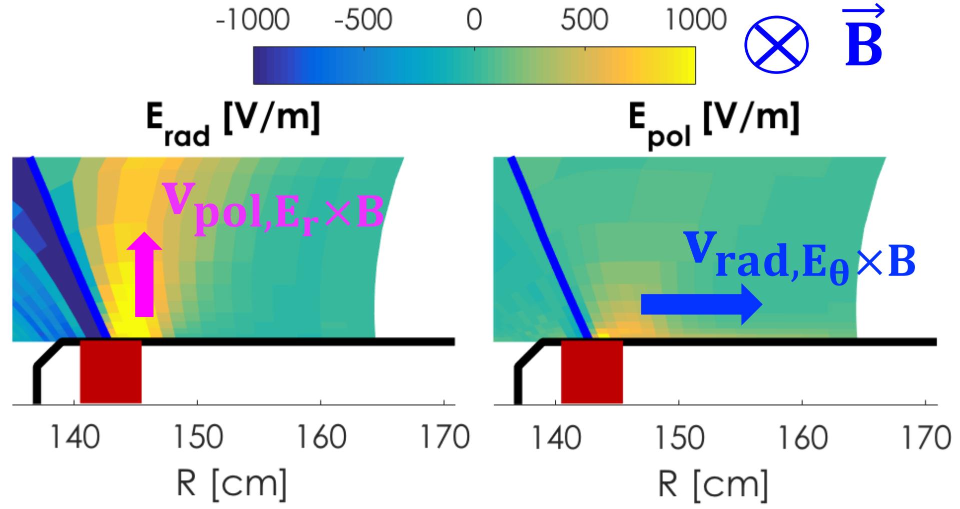

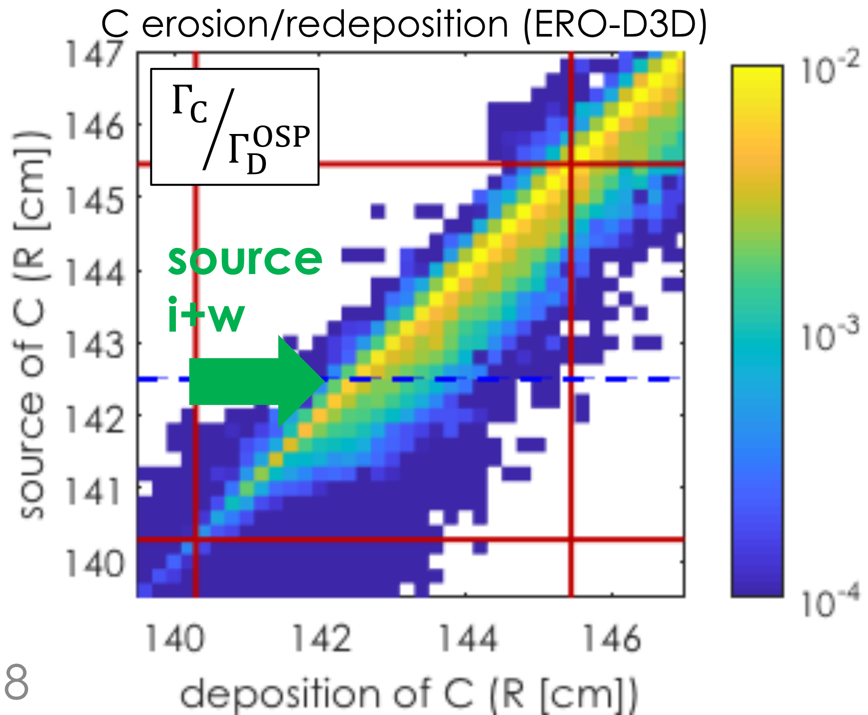

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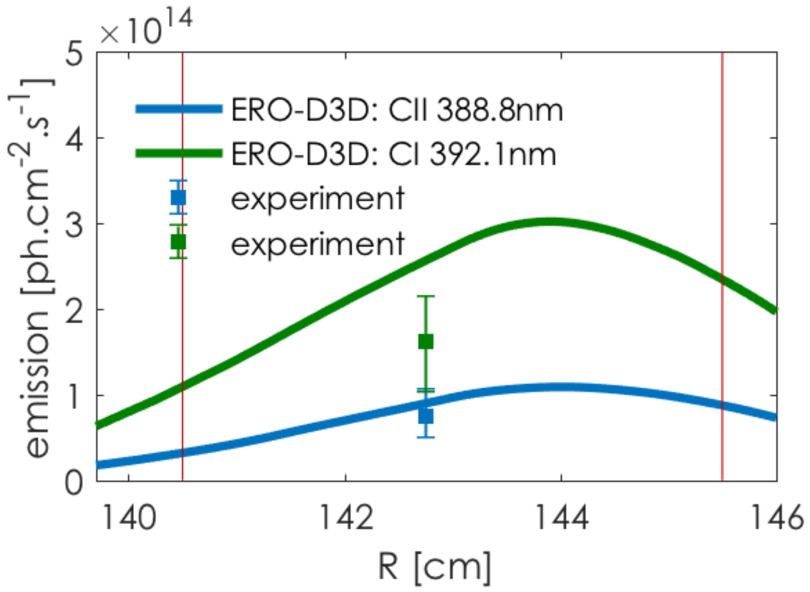

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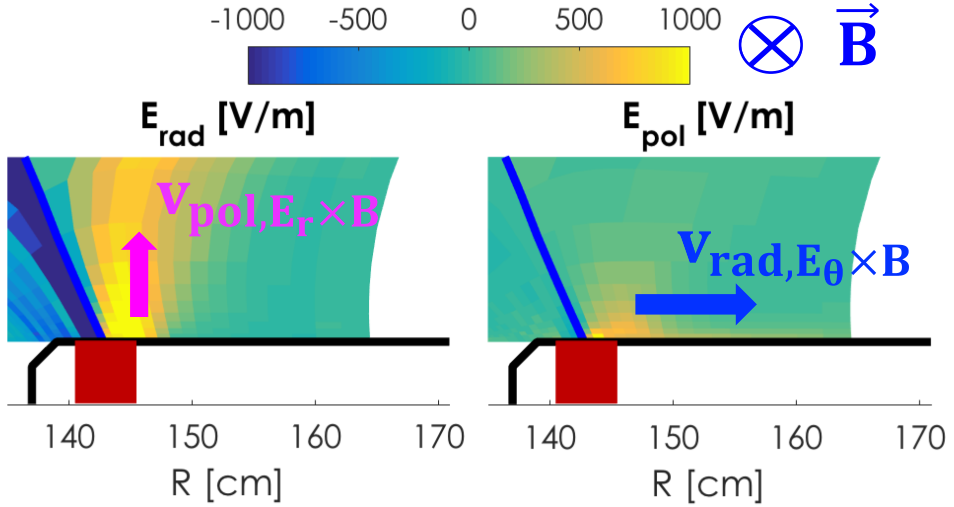

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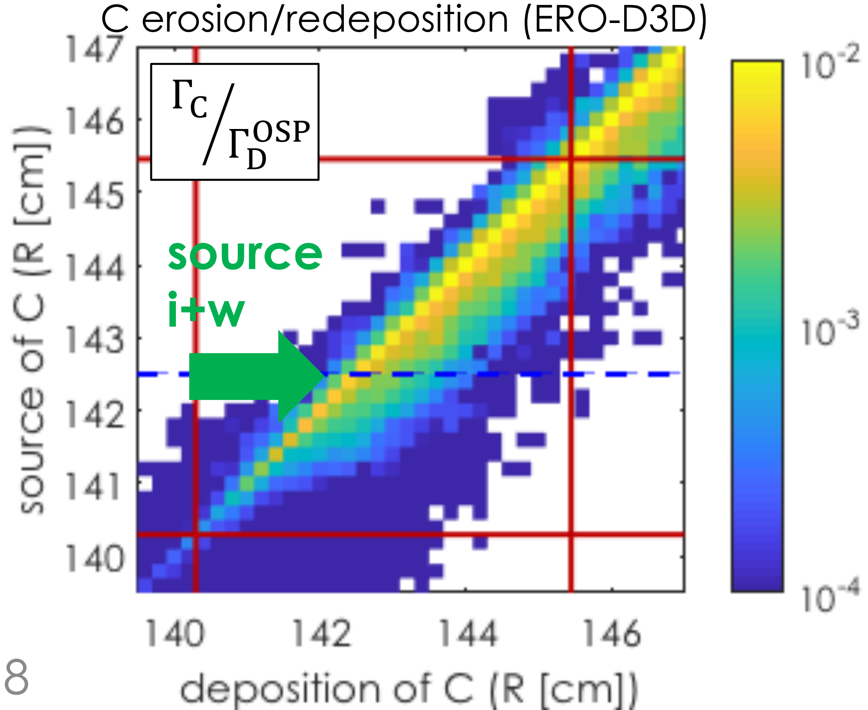
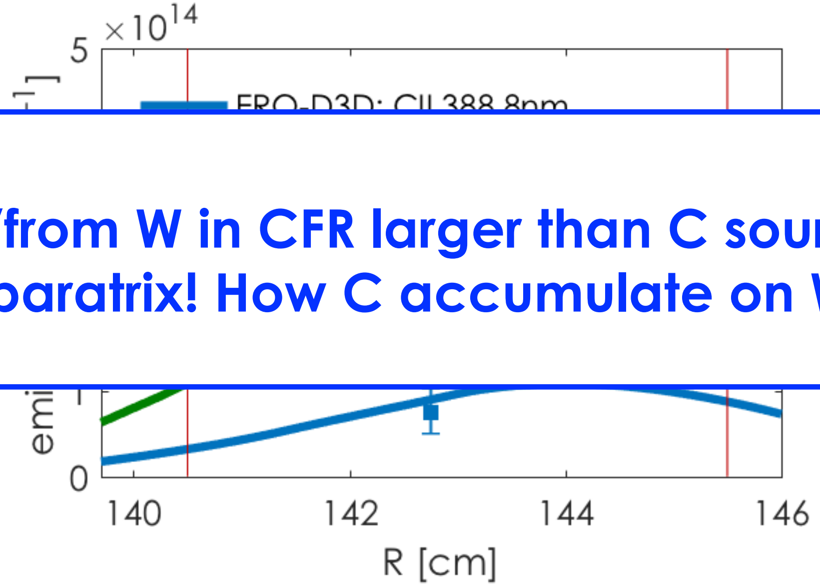


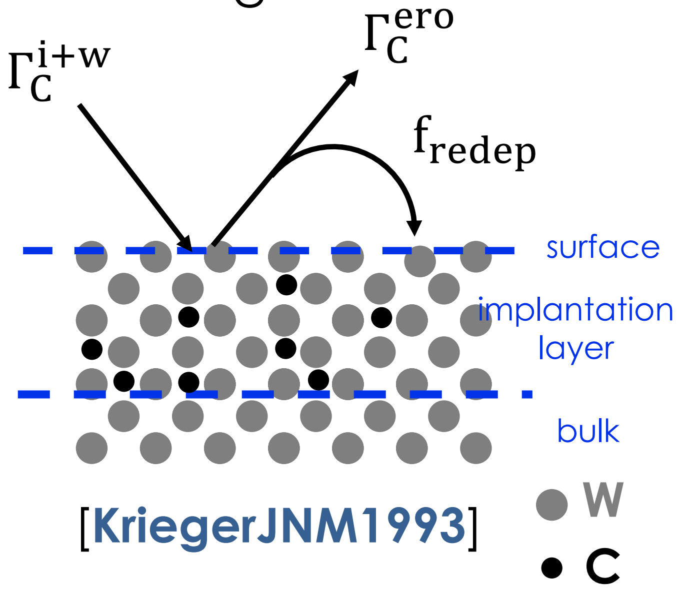


C flow onto/from W in CFR larger than C source near the separatrix! How C accumulate on W?

Implantation of C in W and large redeposition of C on W induces large C flux on W

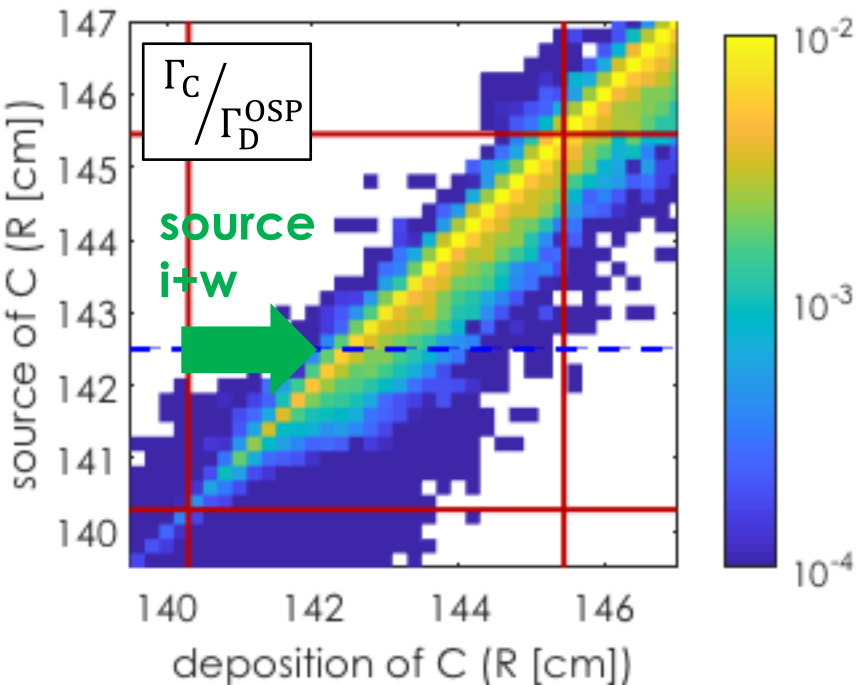
- C implantation in W described by the homogenous mixed material model in ERO-D3D

$$\Gamma_C^{influx} = \frac{\Gamma_C^{i+w}}{1-f_{redep}} > \Gamma_C^{i+w}$$



[KriegerJNM1993]

C erosion/redeposition (ERO-D3D)



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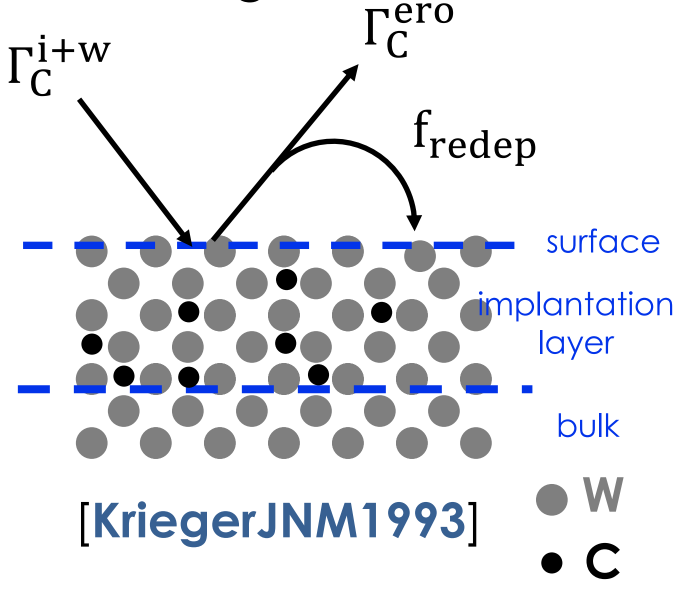

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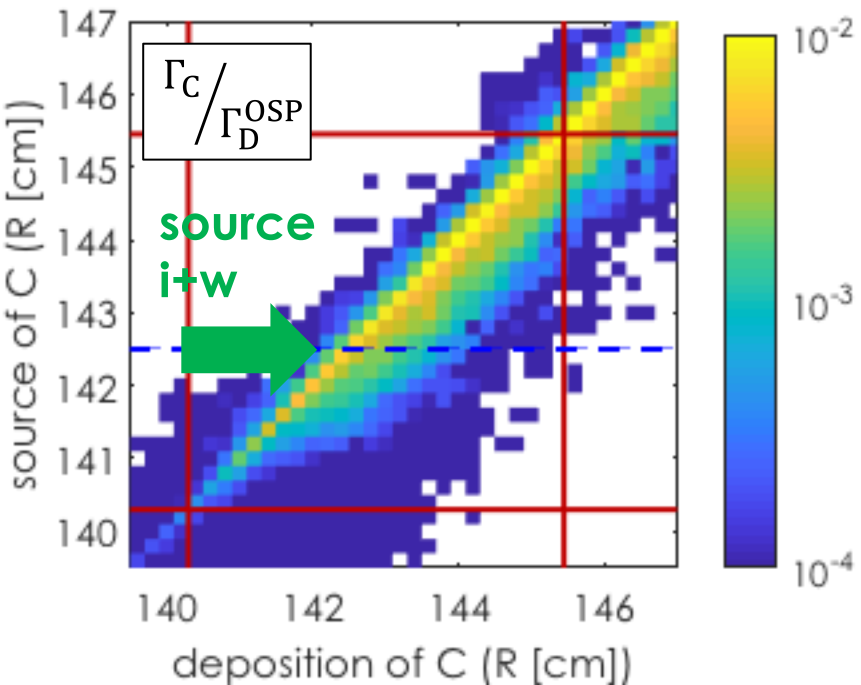
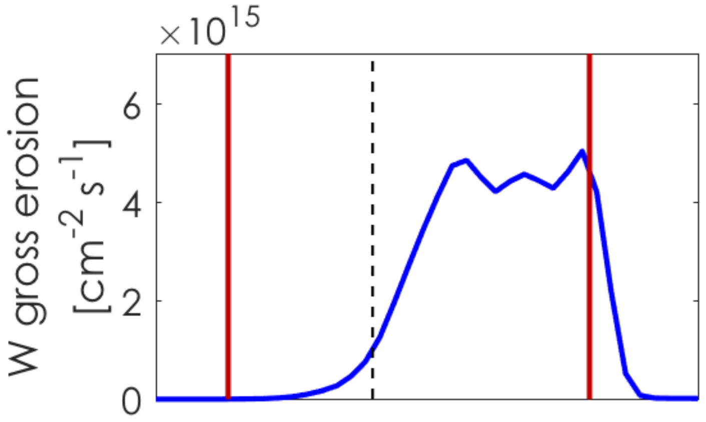


- **Implantation of C in W and large C redeposition onto W induces large C flux on W (C "recycling")**

Implantation of C in W and large redeposition of C on W induces large C flux on W



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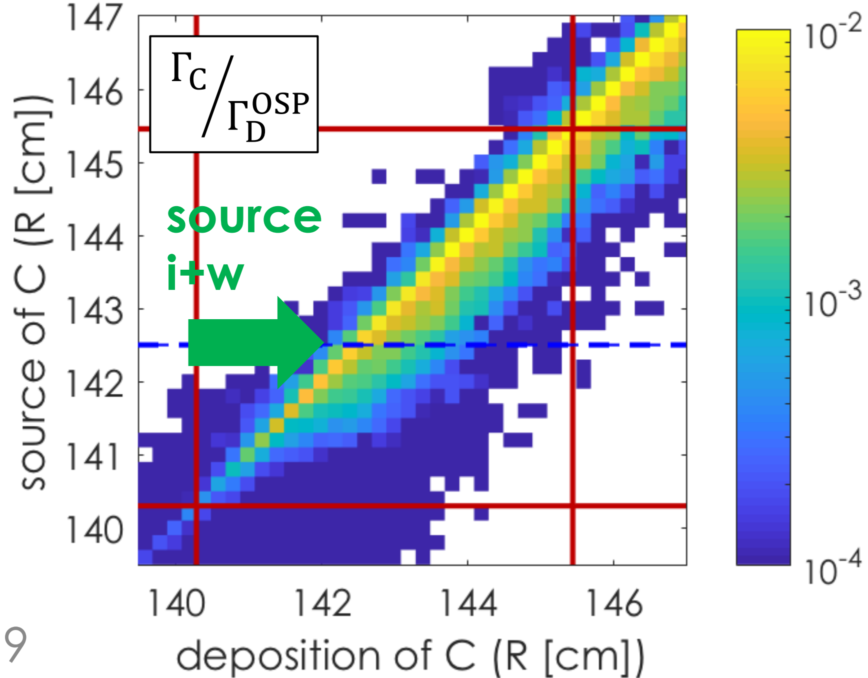

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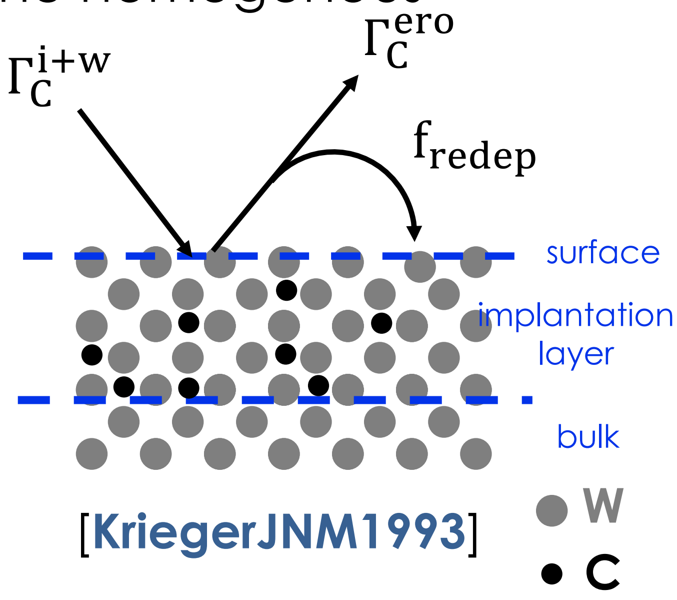

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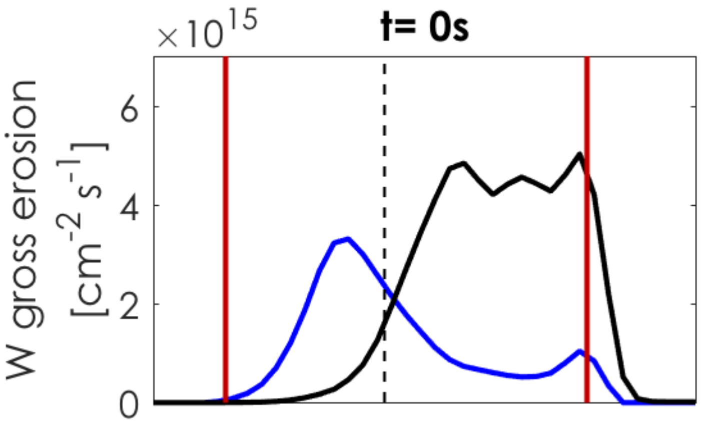

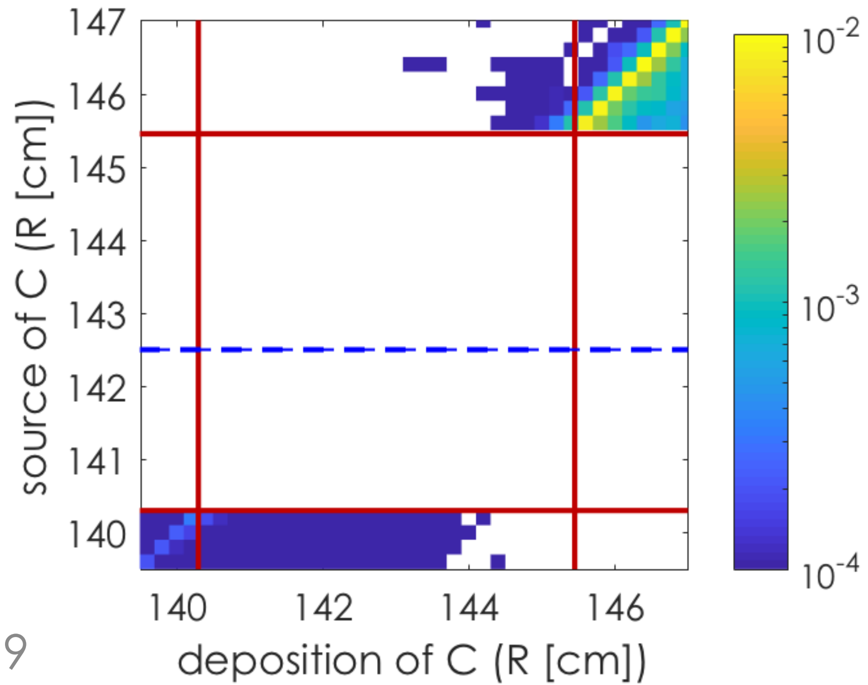

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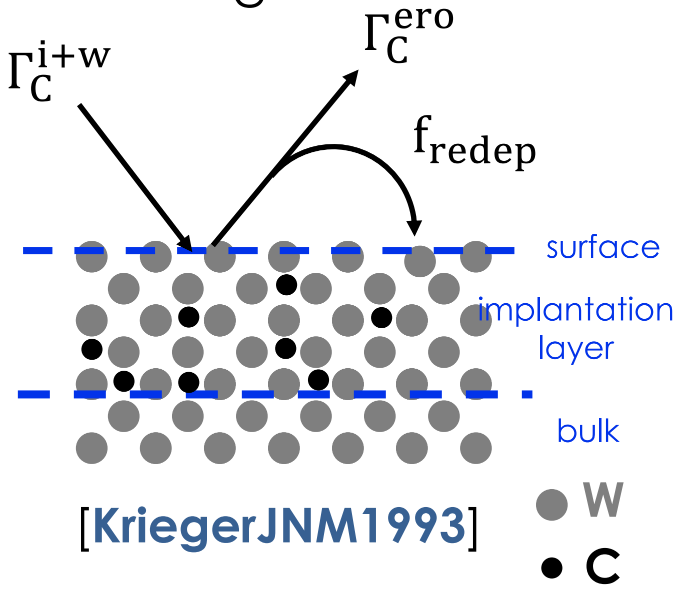

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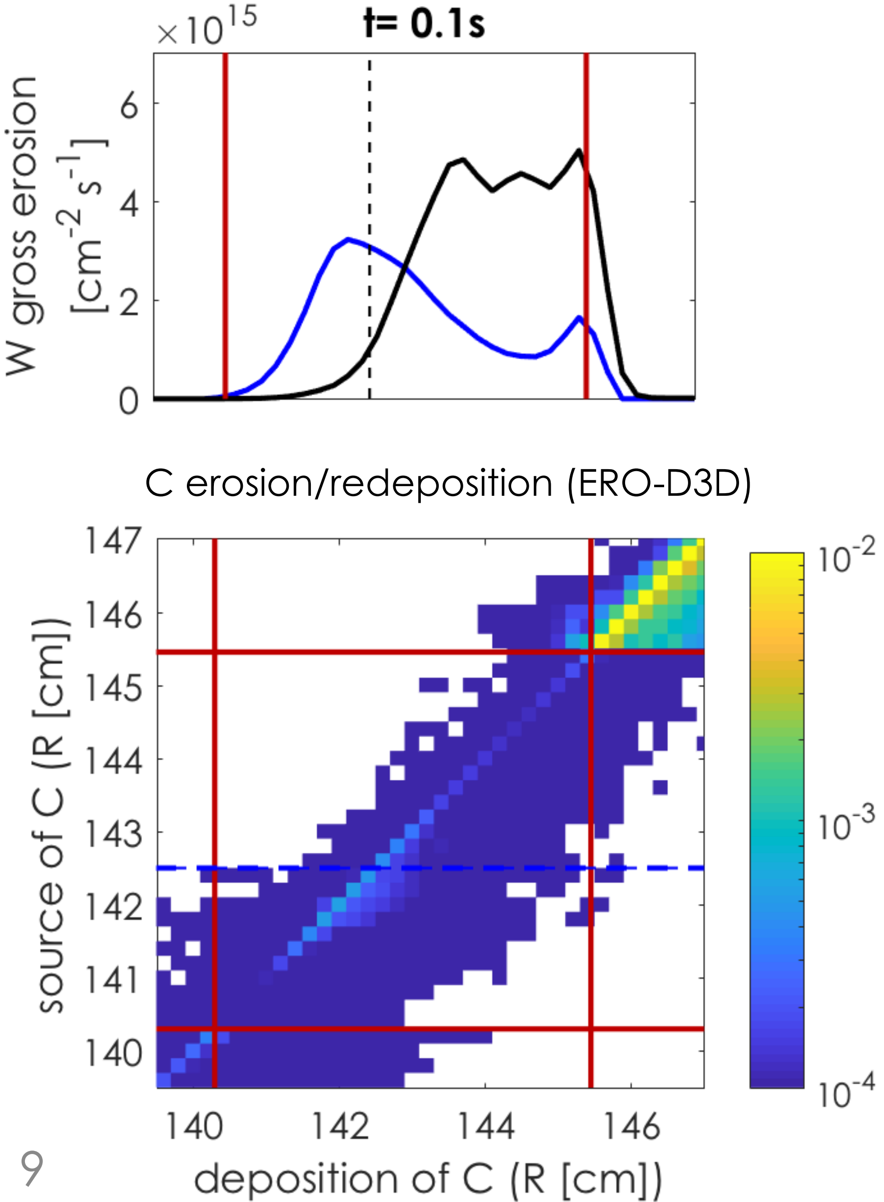

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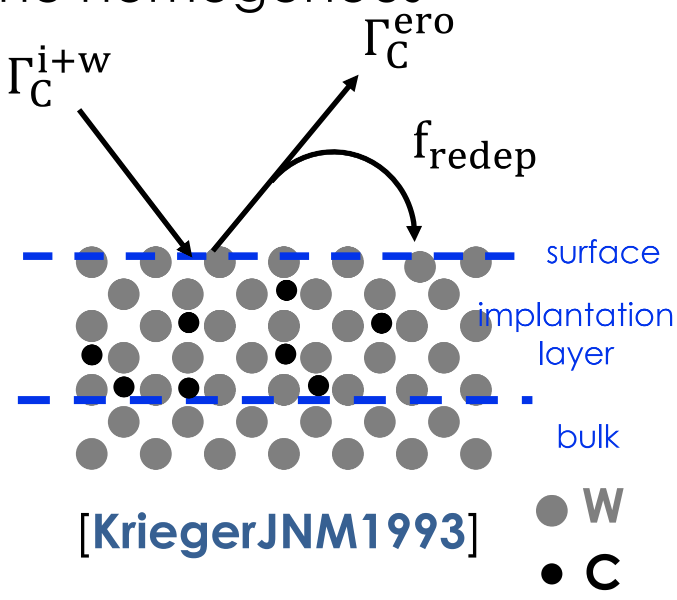

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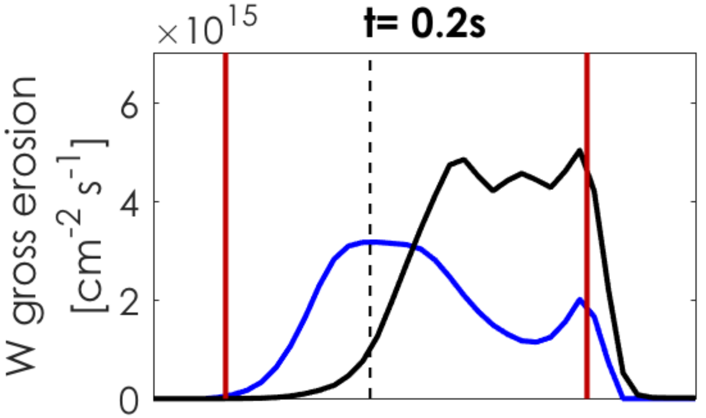

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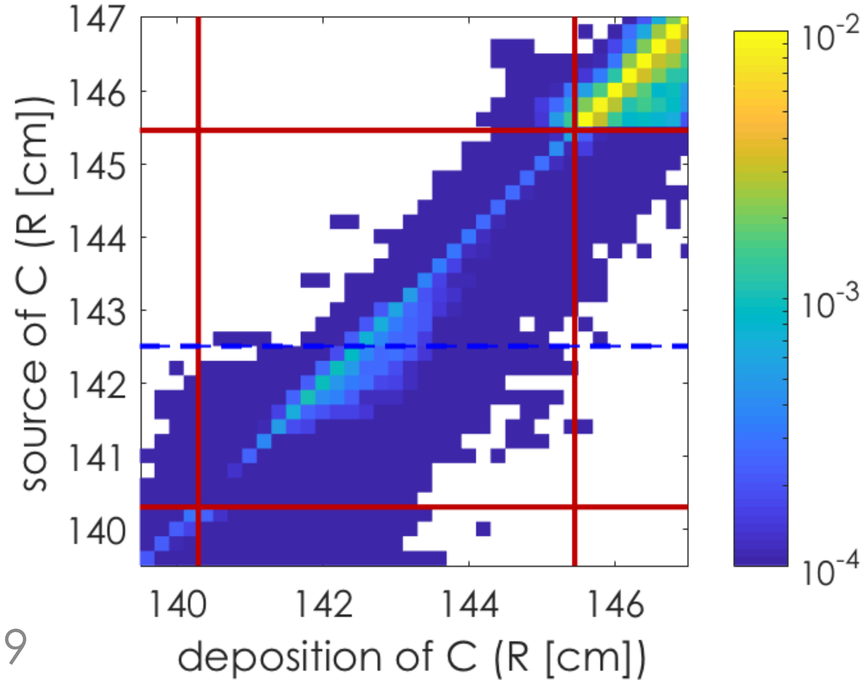

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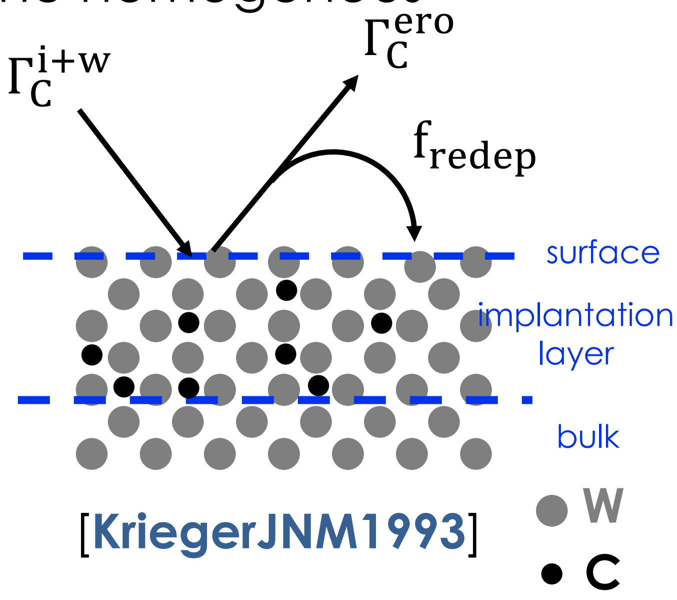

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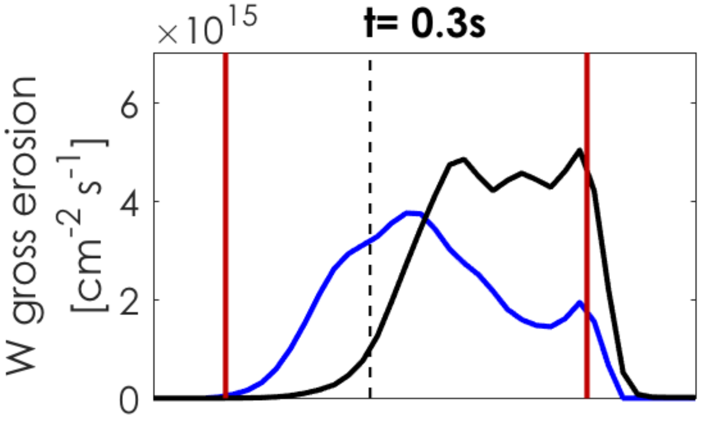

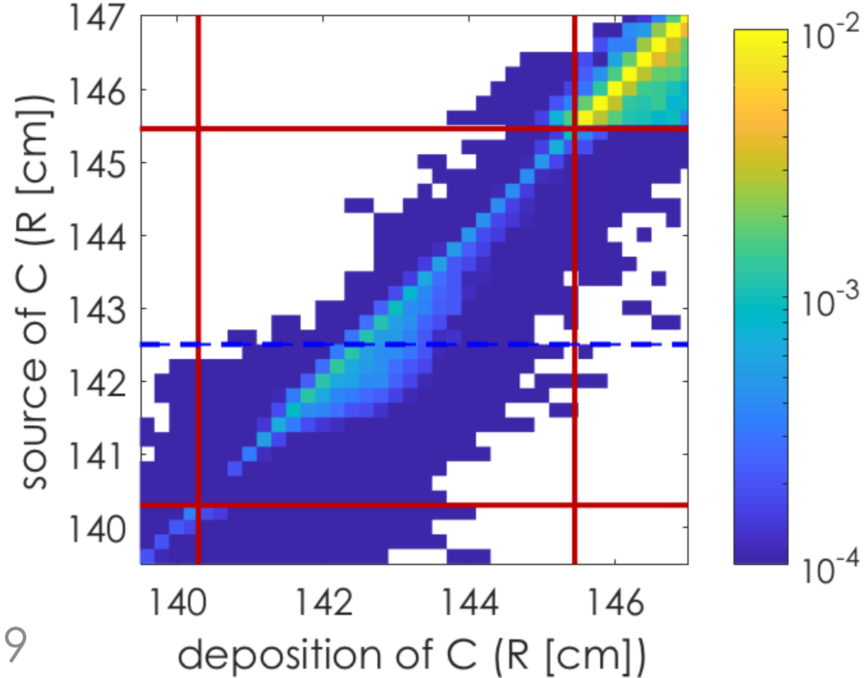

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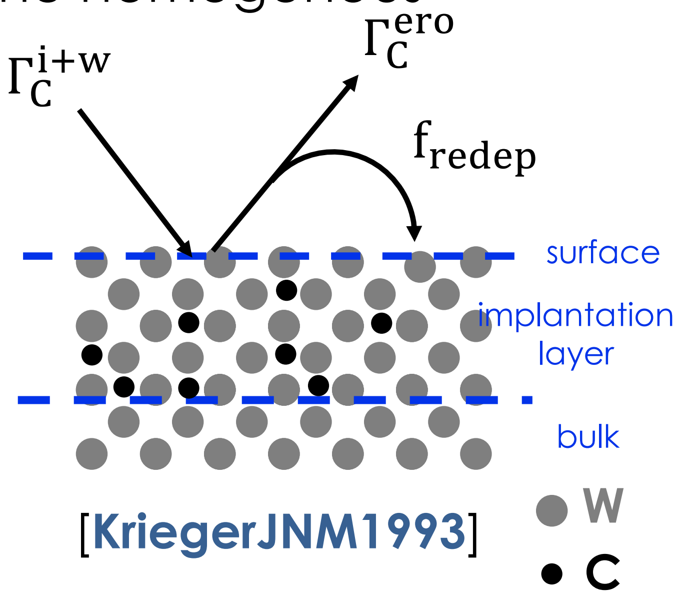

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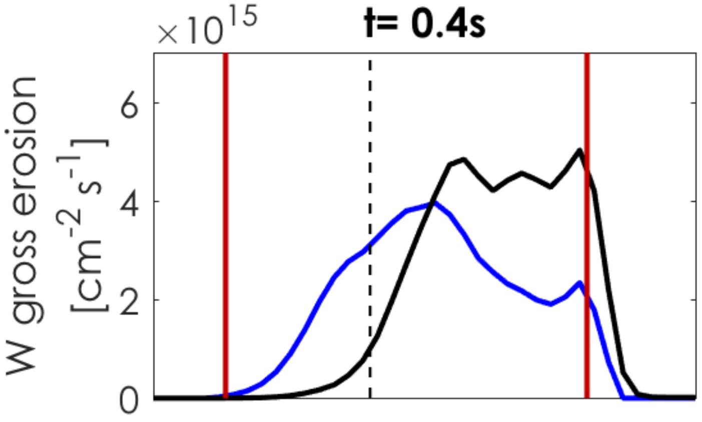

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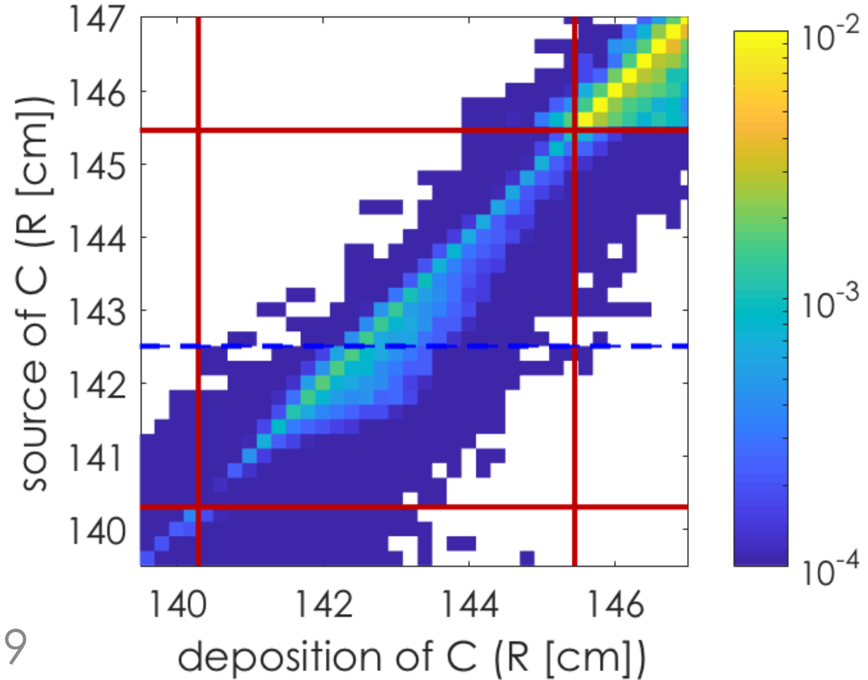

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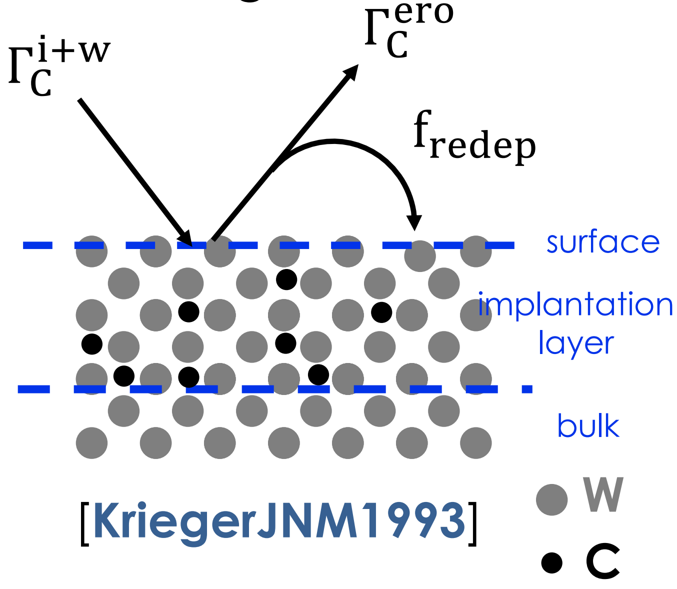

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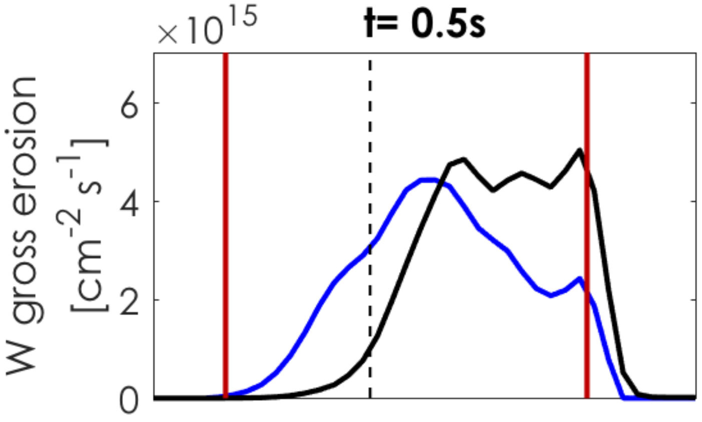

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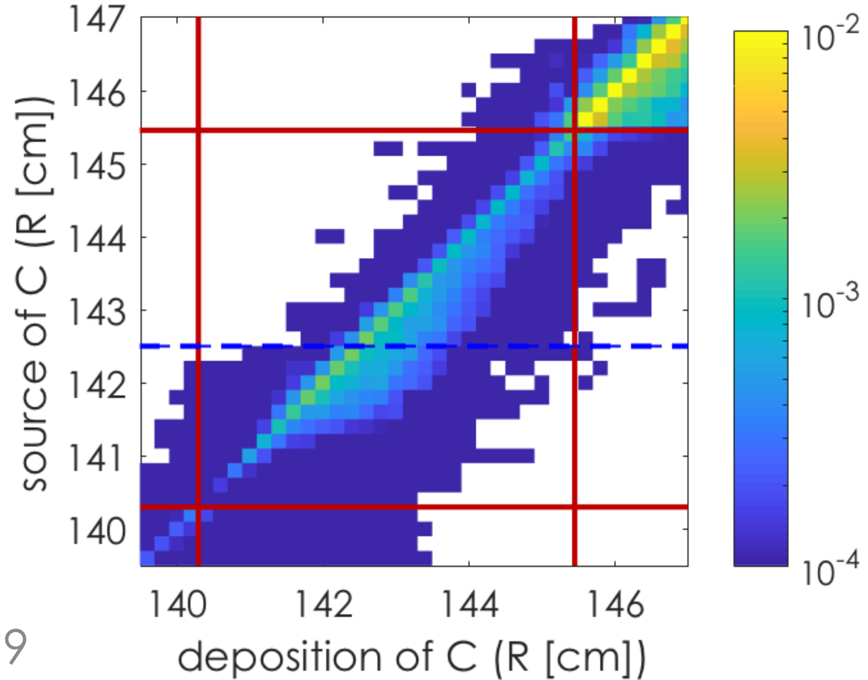

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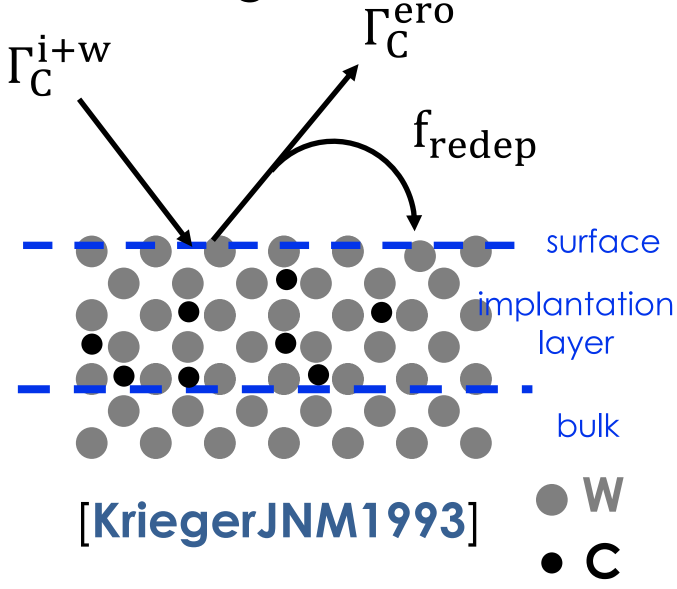

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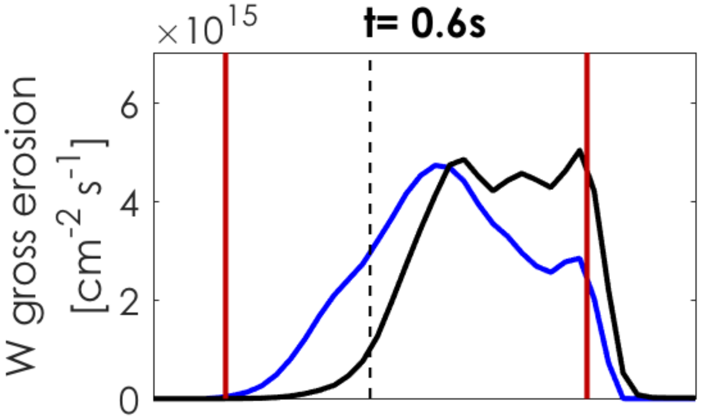

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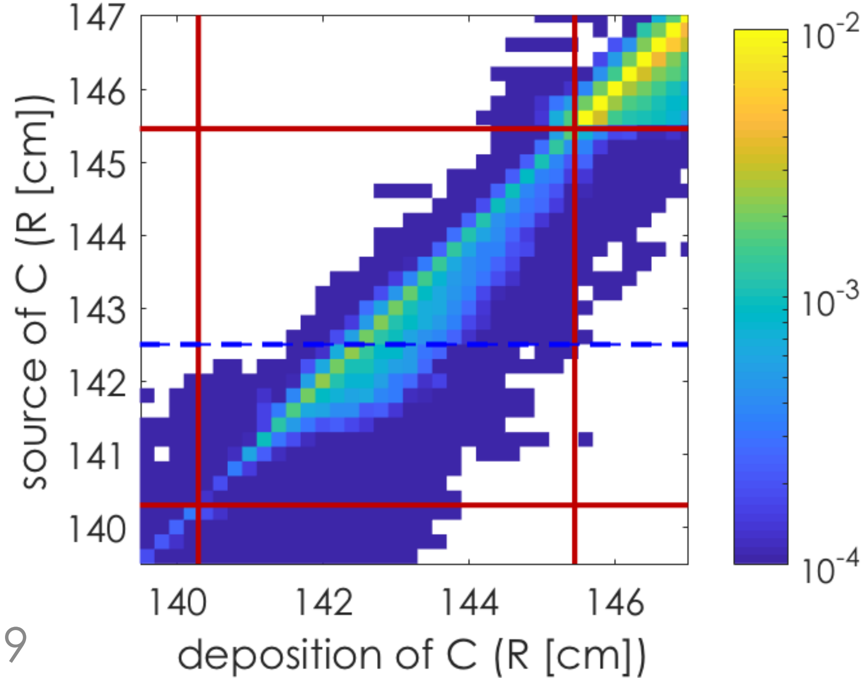

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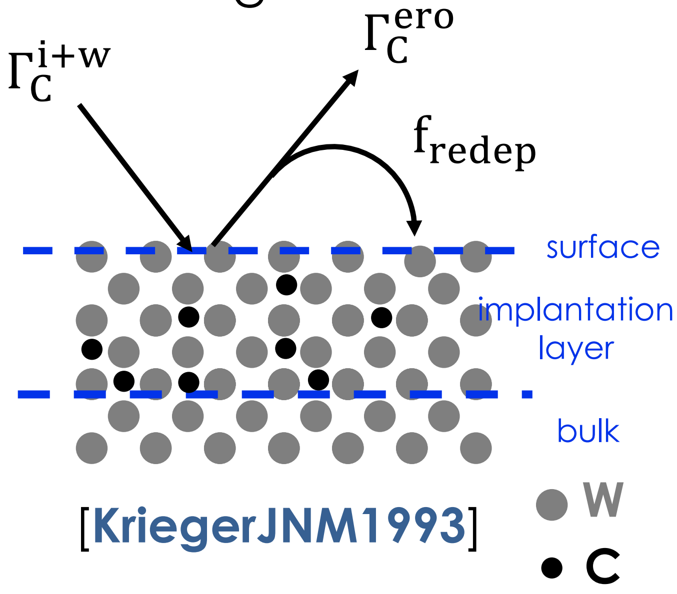

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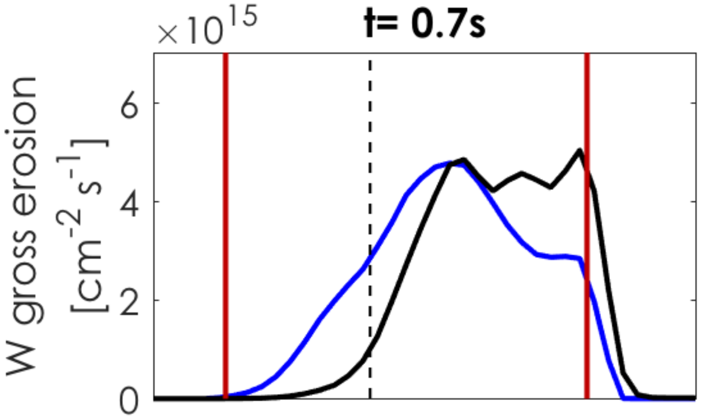

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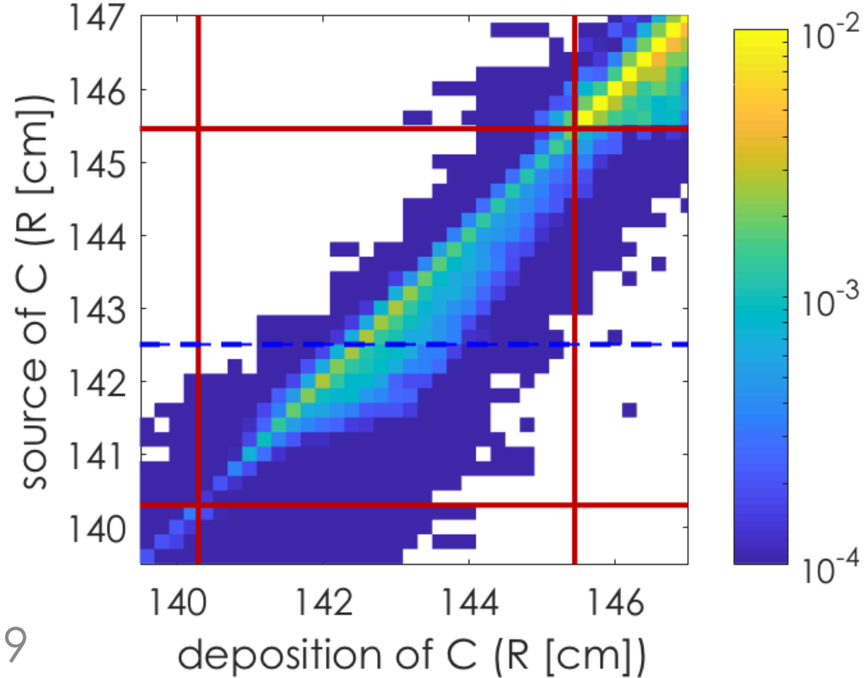

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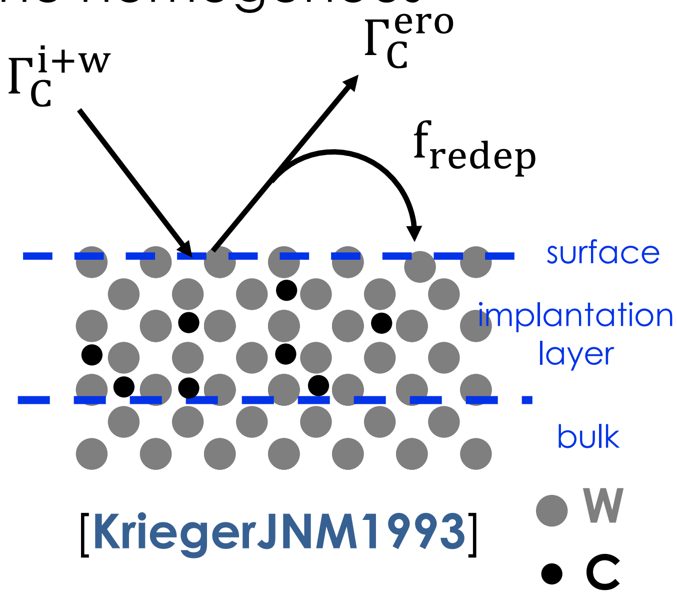

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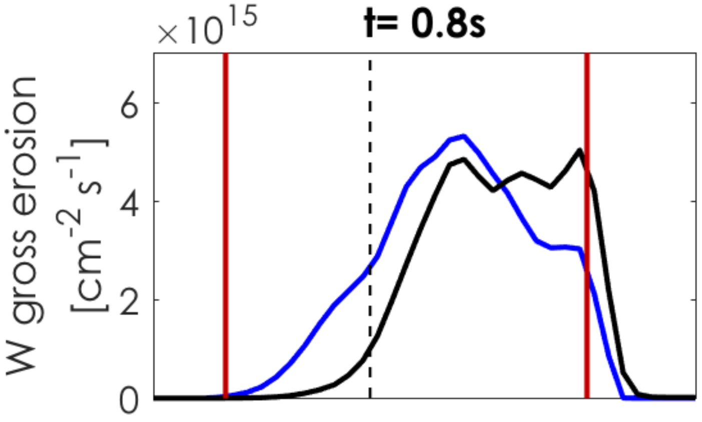

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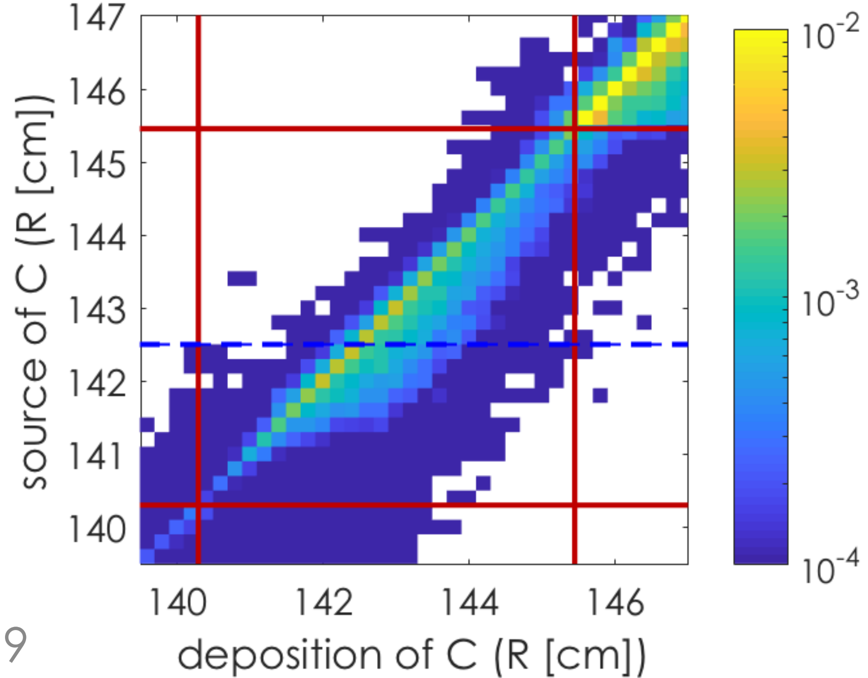

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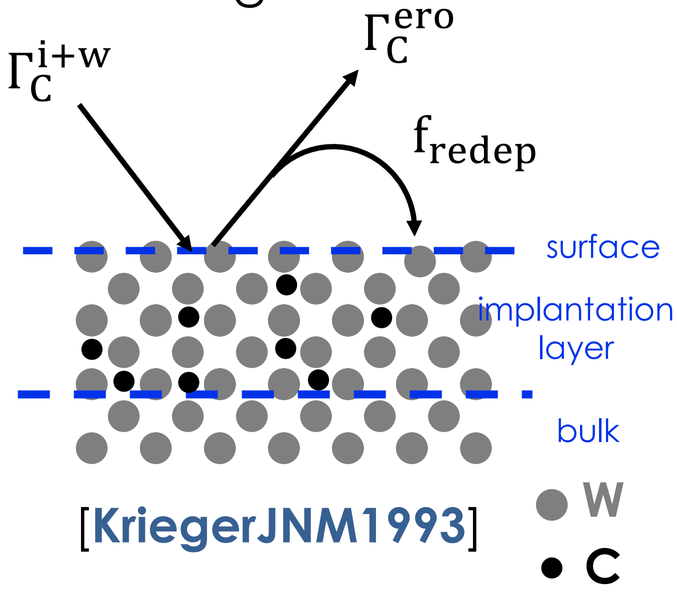

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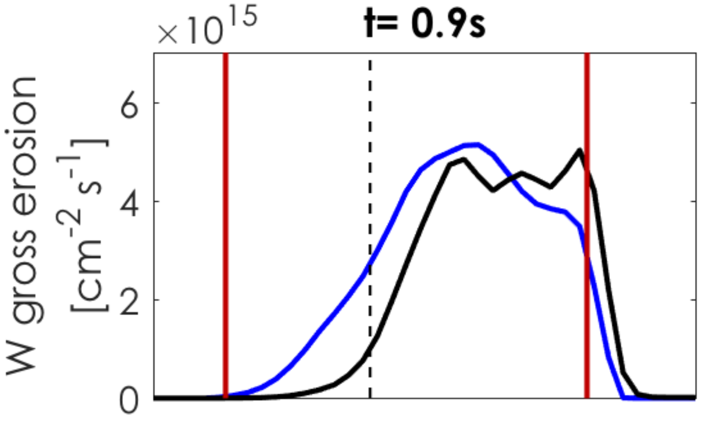

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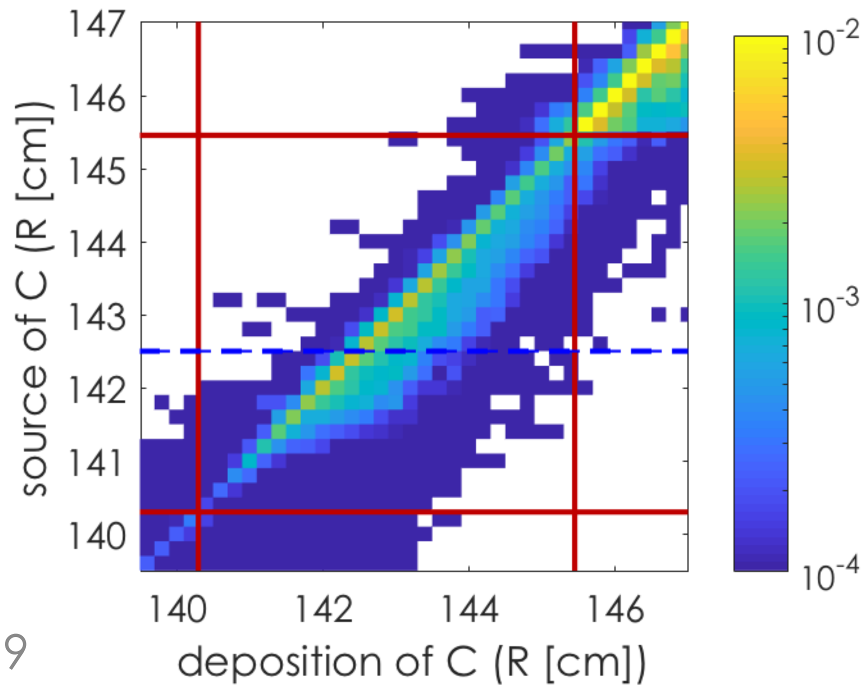

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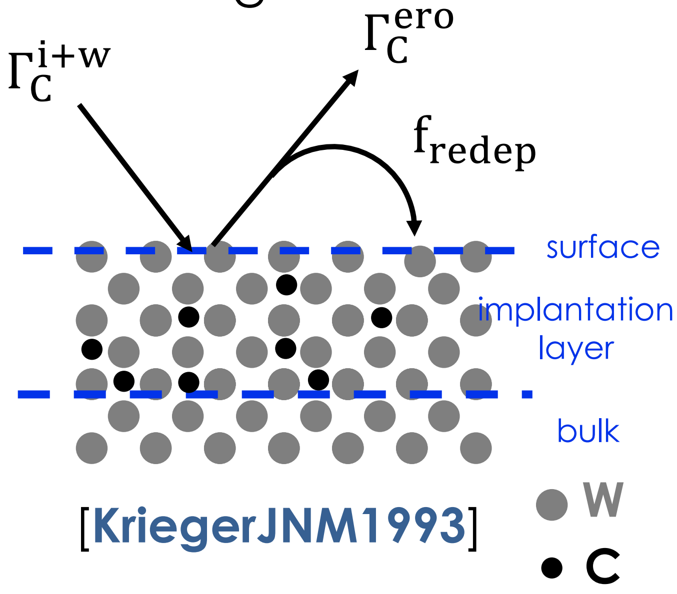

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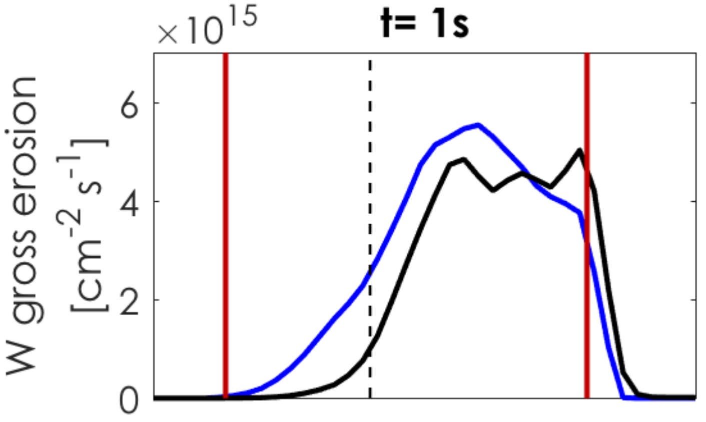

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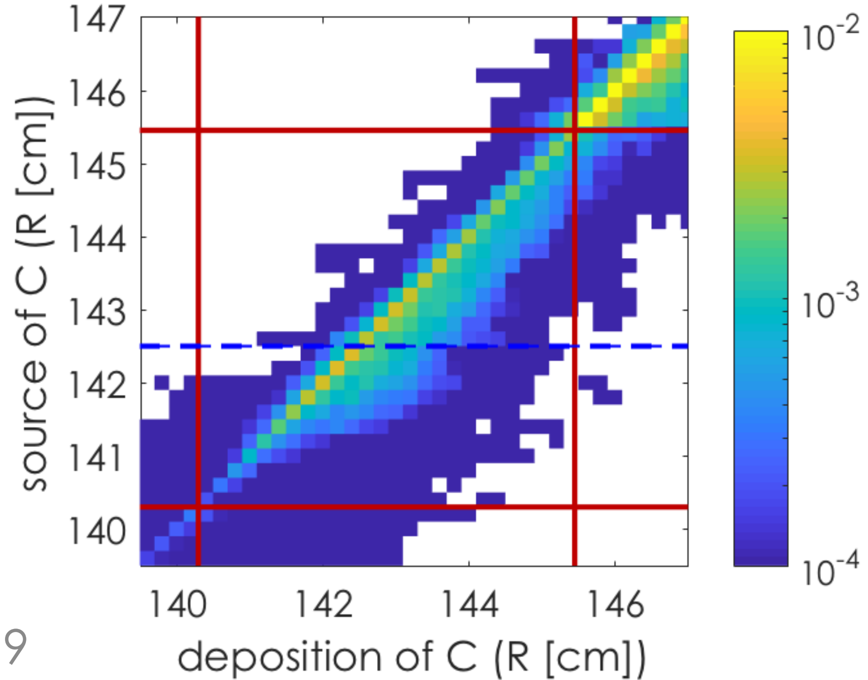

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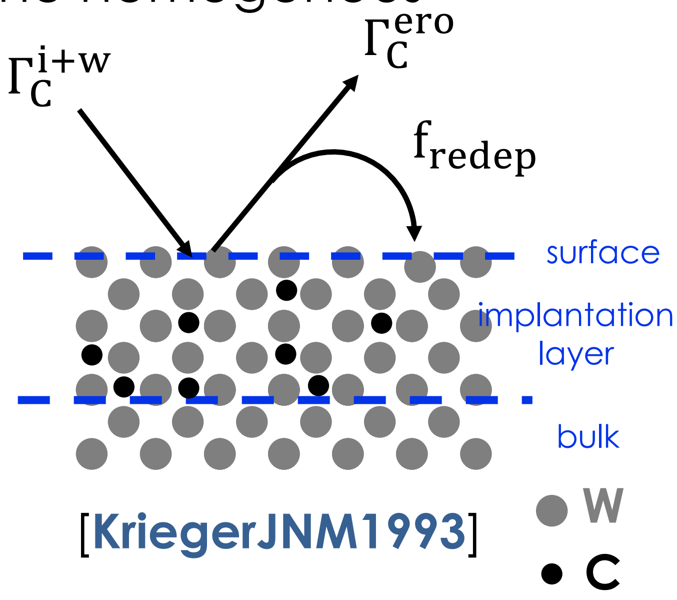

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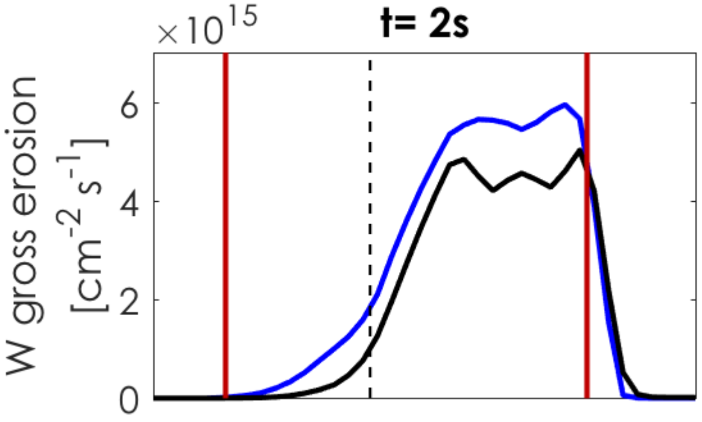

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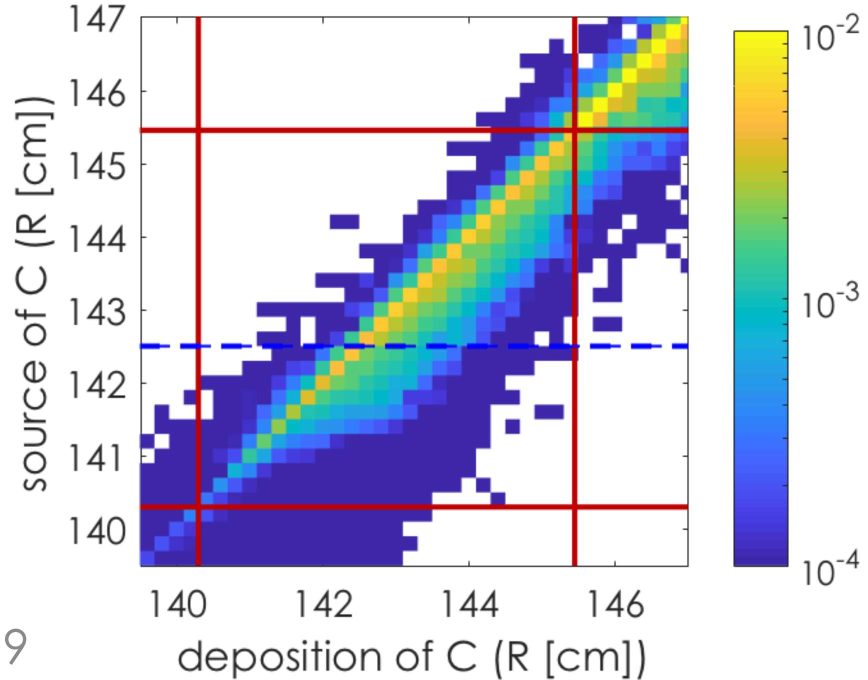

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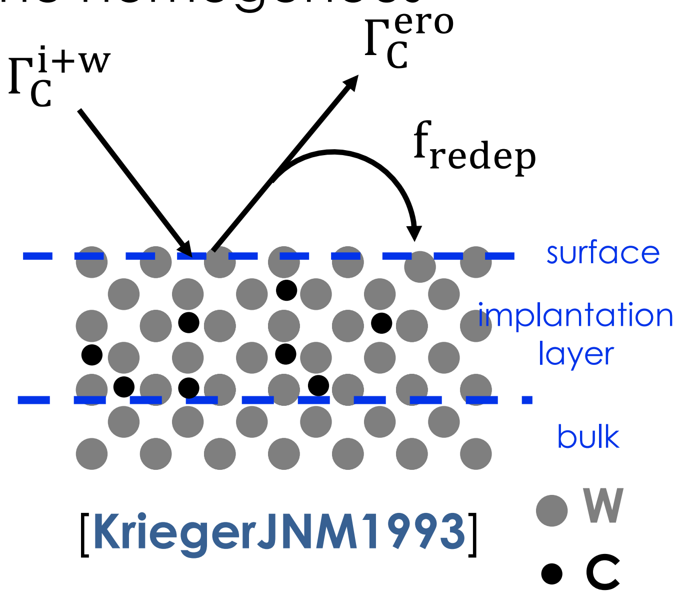

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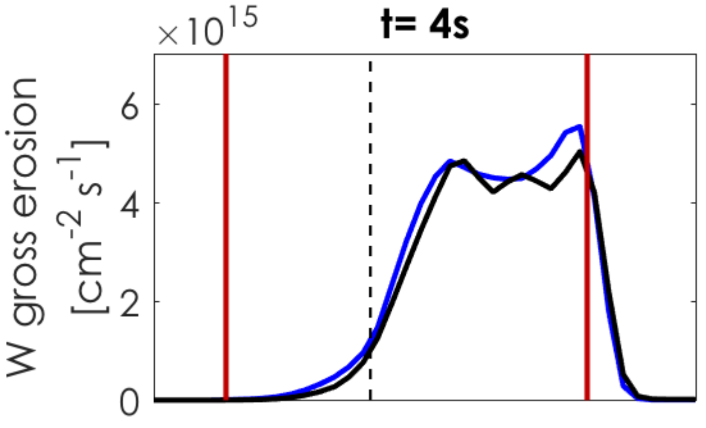

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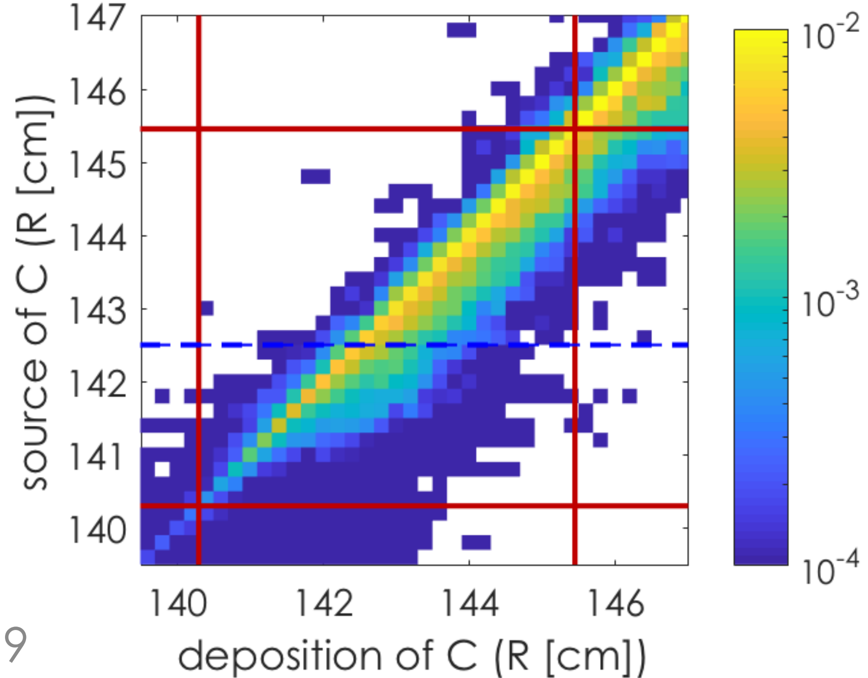

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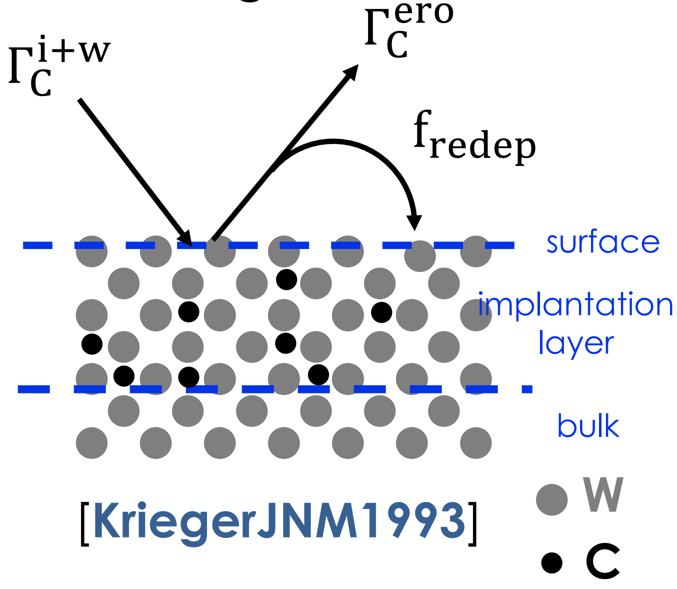

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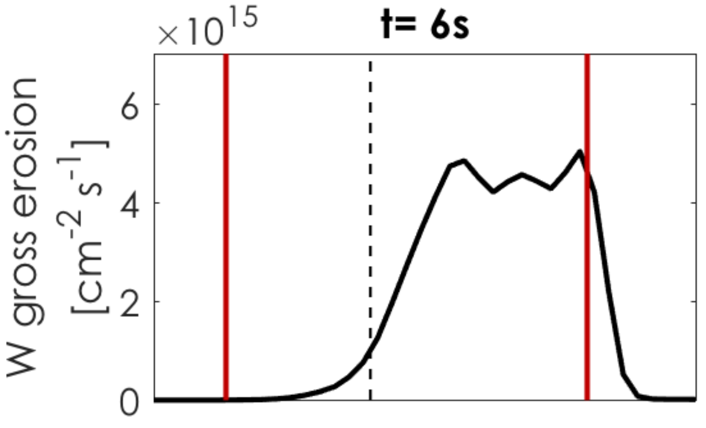

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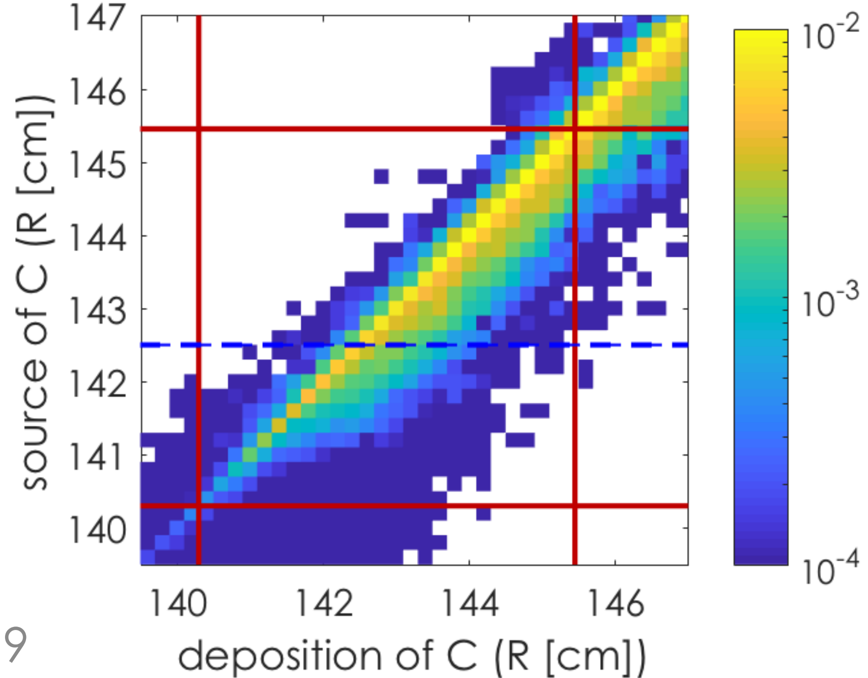

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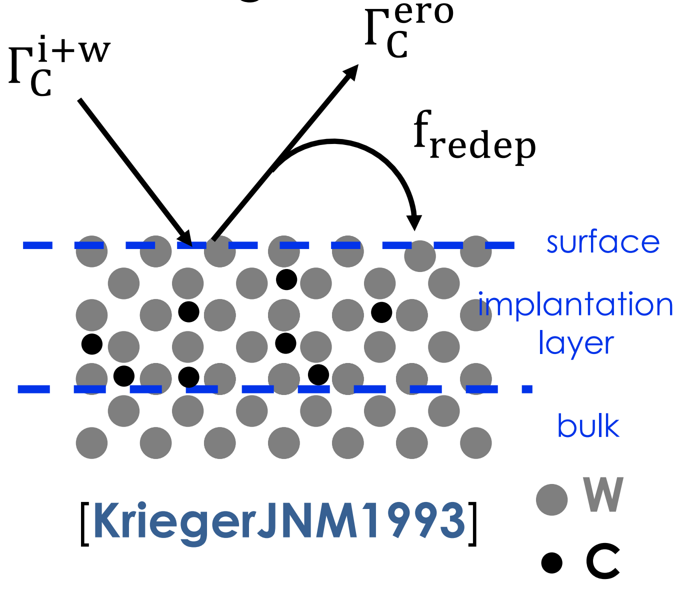

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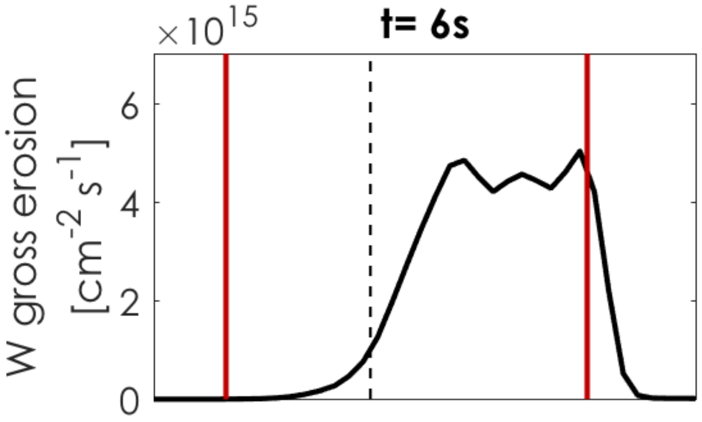

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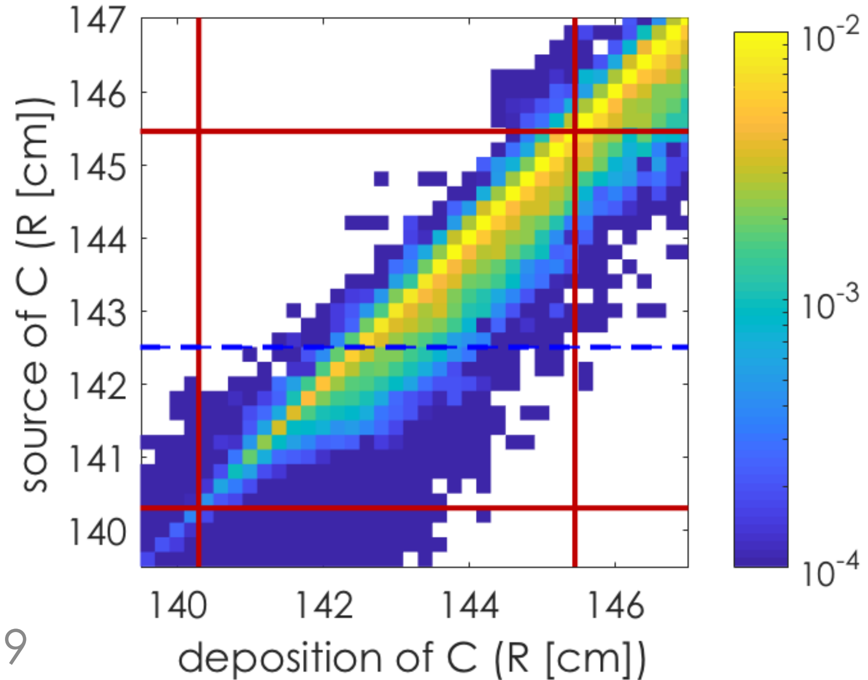

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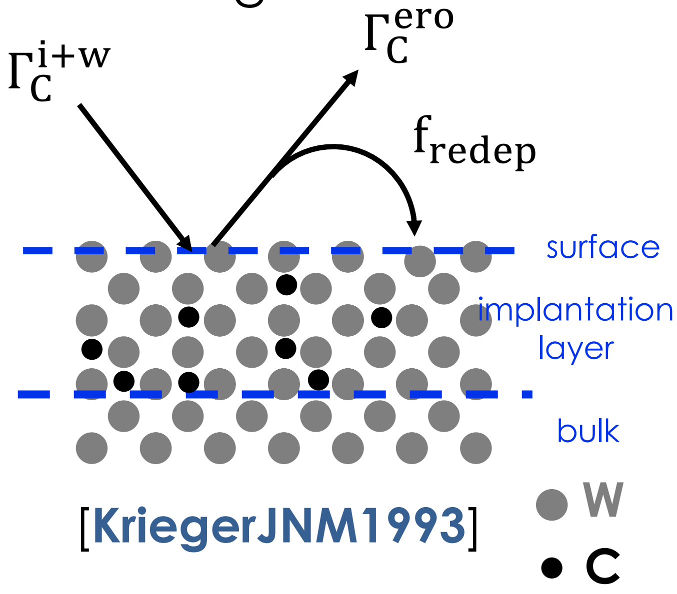

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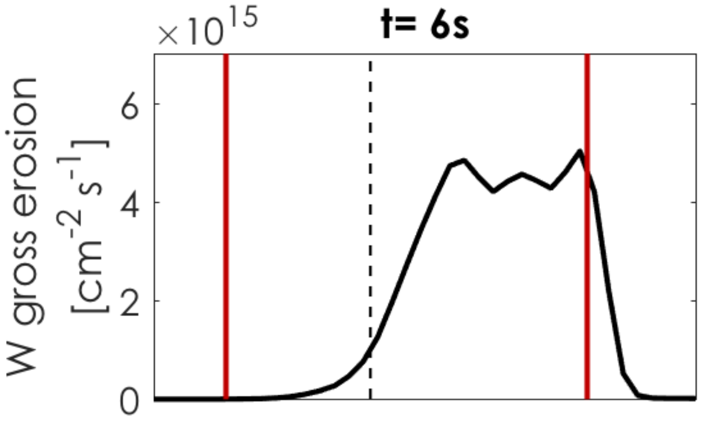

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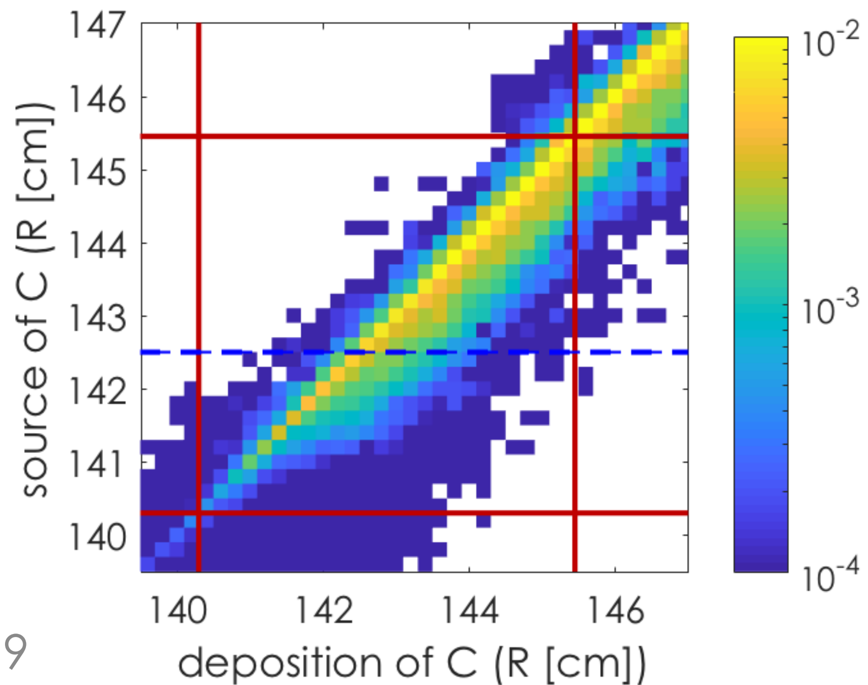

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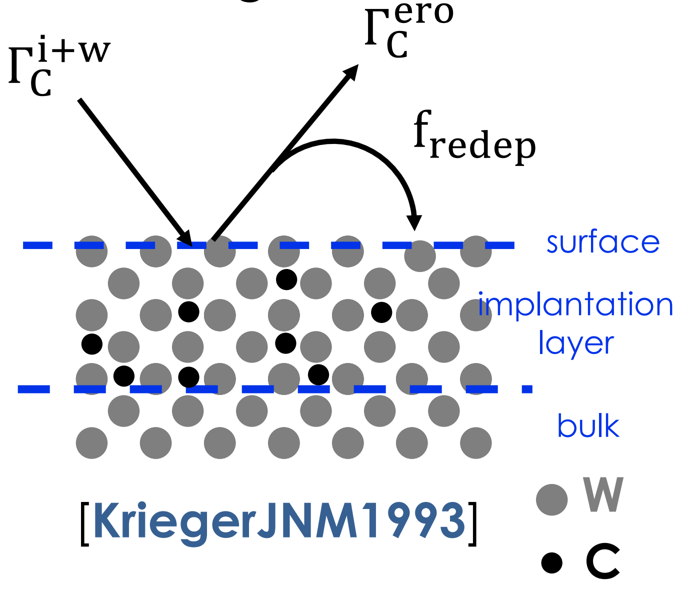

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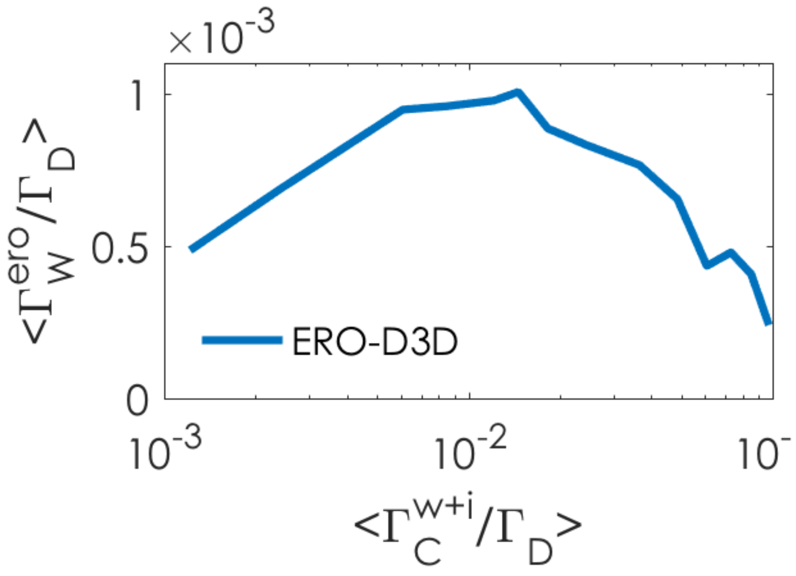
- **Is this model actually robust against uncertainties?**

W gross erosion weakly vary with C source due to the interplay between W sputtering by C and C implantation in W

- **Weak dependency of W gross erosion on C source due to interplay between C implantation in W and W sputtering by C: model robust against uncertainties in C source!**
  - Within the homogenous mixed material model:

$$<\frac{\Gamma_W^{ero}}{\Gamma_D}> \sim \left(1 - \frac{<\frac{\Gamma_C^{w+i}}{\Gamma_D}>}{<\frac{\Gamma_C^{w+i}}{\Gamma_D}> Y_{C\to C} + Y_{D\to C}(1-f_{redep})}\right) \times \left(Y_{D\to W} + \frac{Y_{C\to C}}{1-f_{redep}} <\frac{\Gamma_C^{w+i}}{\Gamma_D}>\right)$$



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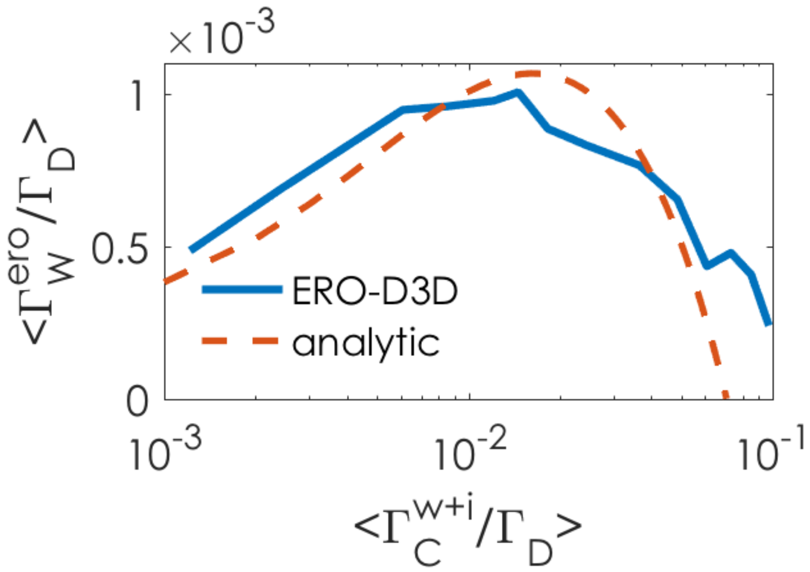

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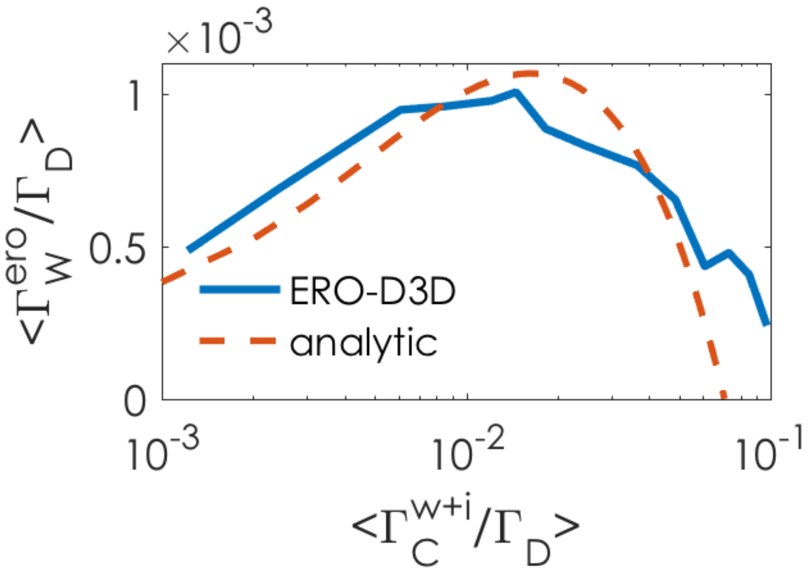
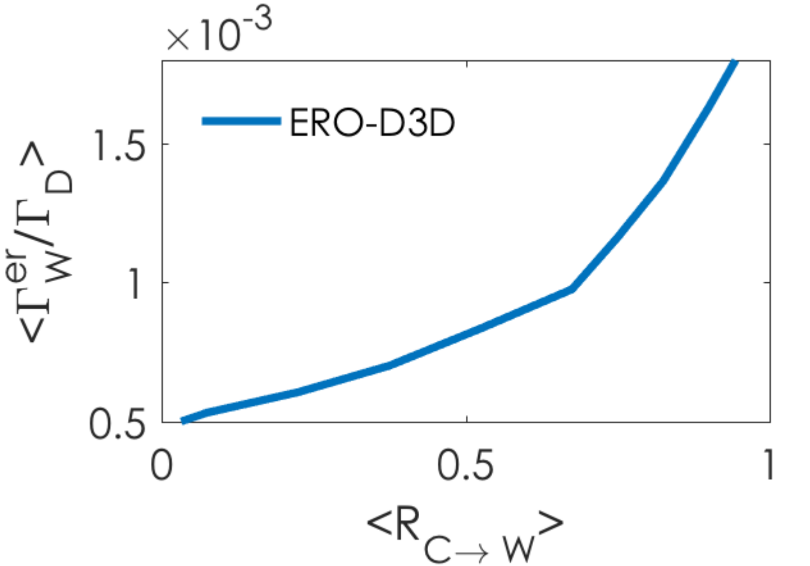


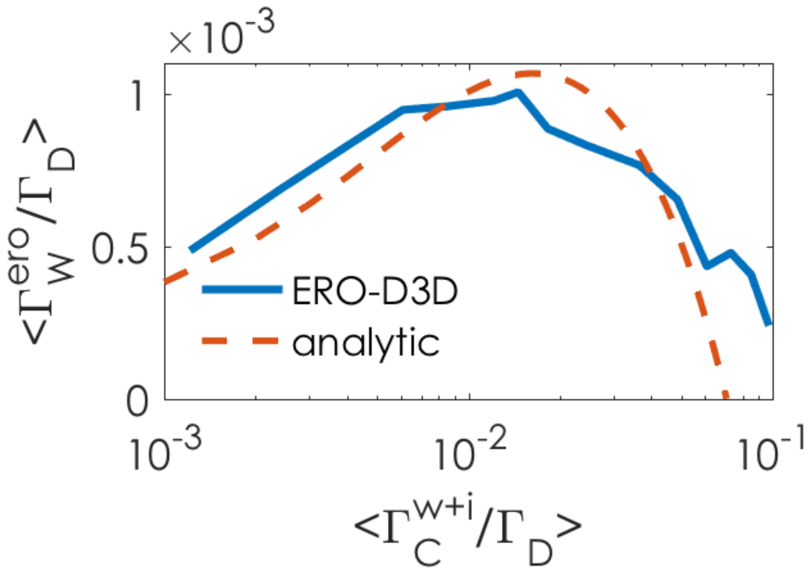
- **C reflection on W strongly enhances W erosion:**
  - Reflection of C on W = sputtering of W + instantaneous re-erosion
  - $R_{C\to W} \sim 0.7 - 0.8 > Y_{D\to C}, Y_{C\to C}$



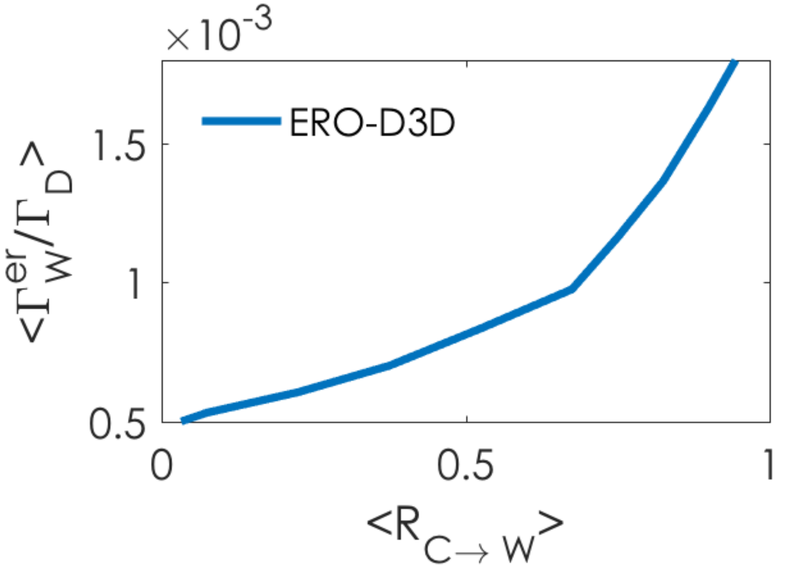
W gross erosion weakly vary with C source due to the interplay between W sputtering by C and C implantation in W

- **Weak dependency of W gross erosion on C source due to interplay between C implantation in W and W sputtering by C: model robust against uncertainties in C source!**
  - Within the homogenous mixed material model:

$$<\frac{\Gamma_W^{ero}}{\Gamma_D}> \sim \left(1 - \frac{<\frac{\Gamma_C^{w+i}}{\Gamma_D}>}{<\frac{\Gamma_C^{w+i}}{\Gamma_D}> Y_{C\to C} + Y_{D\to C}(1-f_{redep})}\right) \times \left(Y_{D\to W} + \frac{Y_{C\to C}}{1-f_{redep}} <\frac{\Gamma_C^{w+i}}{\Gamma_D}>\right)$$



- **C reflection on W strongly enhances W erosion:**
  - Reflection of C on W = sputtering of W + instantaneous re-erosion
  - $R_{C\to W} \sim 0.7 - 0.8 > Y_{D\to C}, Y_{C\to C}$



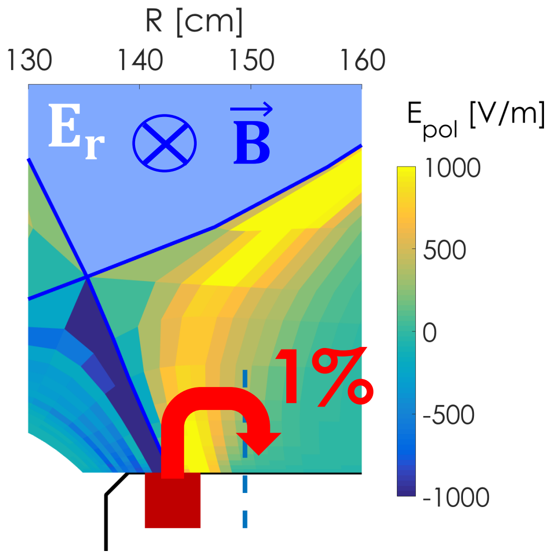
W gross erosion induced by large C flux on W resulting from interplay between ExB drifts, C implantation/redeposition & reflection on W

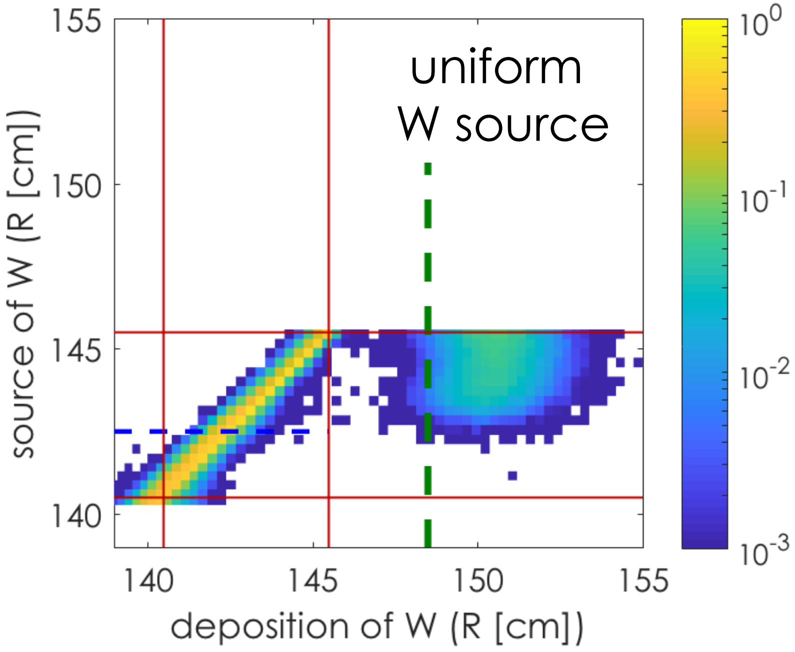
Modeling of C and W erosion/redeposition in DIII-D divertor

- Introduction
  - Why modeling W net erosion is challenging?
  - Measurement of W gross erosion and outboard deposition in DIII-D lower divertor with a toroidally symmetric W source
- Modeling and analysis of W gross erosion mechanism
  - W sputtering results from synergetic effects between impurity erosion, implantation, redeposition and transport processes
- Modeling and analysis of outboard W deposition mechanism
  - W net erosion may be inferred from W deposition measurements

Outboard W deposition due to interplay between poloidal and radial ExB drifts and may be used to quantify W net erosion

- Experiment: **localized** W deposition $\mathbf{\Gamma_W^{dep} \sim 0.01 \times \Gamma_W^{ero}}$ at 3.5cm from W outer edge
- **Outboard W deposition qualitatively reproduced with ERO-D3D**





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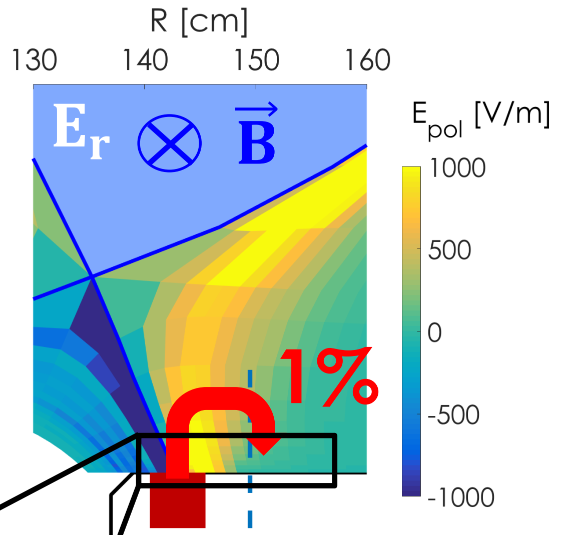
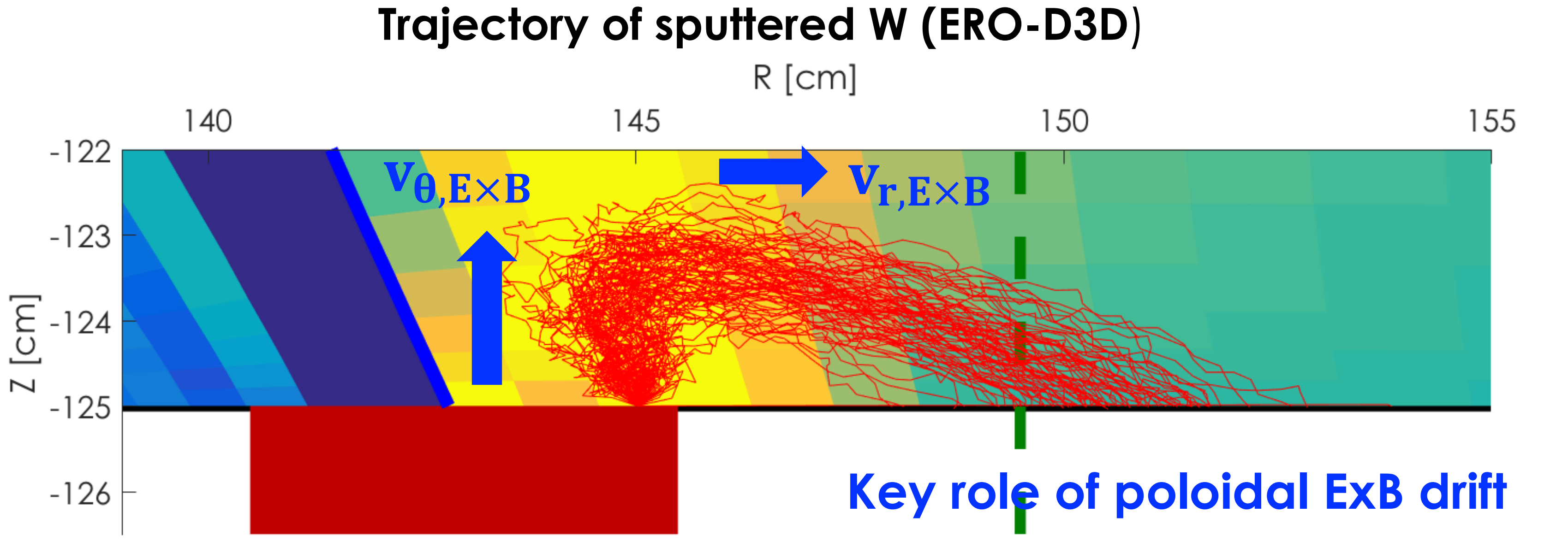
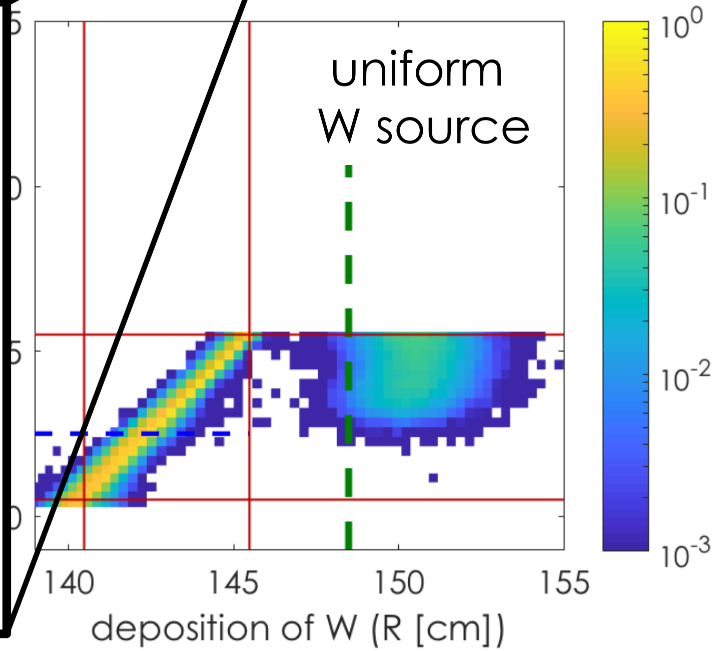
  - Radial W migration due interplay between <u>outward</u> radial ExB drift and <u>upward</u> poloidal ExB drift (balance friction with D)
  - Most of W not redeposited locally are deposited outboard







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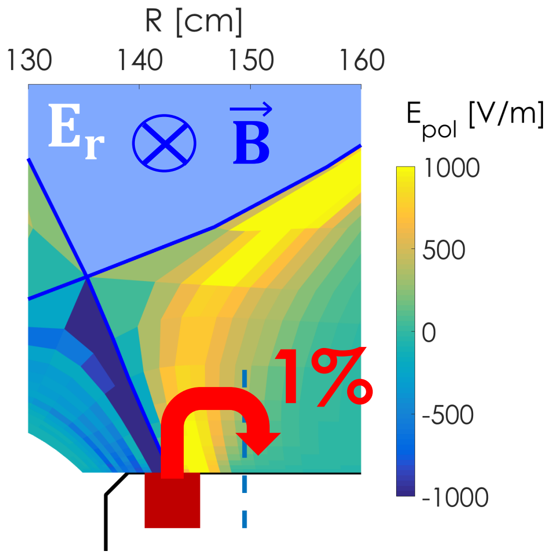
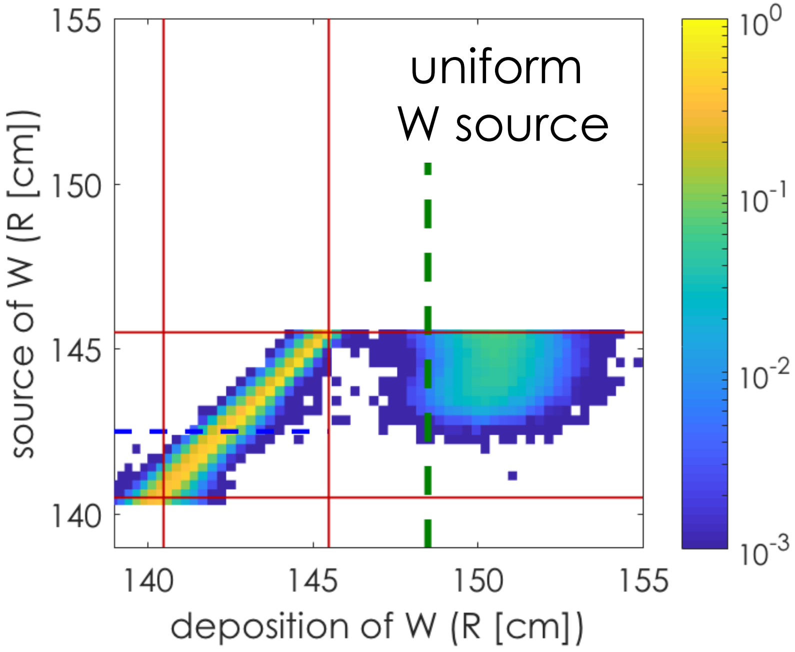


- **Measurement of W outboard deposition may help to quantify W net erosion…**
  - But accurate quantitative modeling difficult due to uncertainties in plasma conditions (e.g. drifts near targets) and W transport (e.g. prompt deposition)



Modeling of C and W erosion/redeposition in DIII-D divertor: conclusions

- **Modeling of W erosion by low-Z impurities and W transport in divertor must include various physical mechanisms (mixed-material effects, ExB drifts, "global" source of low-Z impurity, reflection) and their synergetic effects to provide full consistency with plasma background conditions**

Modeling of C and W erosion/redeposition in DIII-D divertor: conclusions

- Modeling of W erosion by low-Z impurities and W transport in divertor must include various physical mechanisms (mixed-material effects, ExB drifts, "global" source of low-Z impurity, reflection) and their synergetic effects to provide full consistency with plasma background conditions

- Reduced model of material erosion with mixed-material (C and W described with the homogenous mixed-material model) sufficiently accurate to model material erosion:

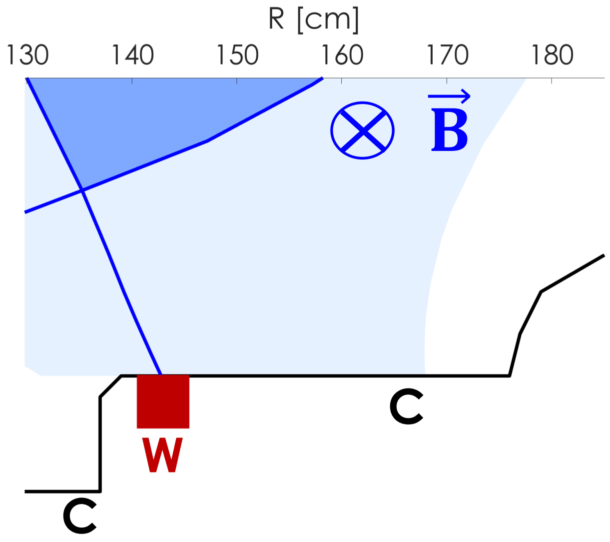
→ It might be very beneficial to implement both reduced models (e.g HMM) and advanced models of material erosion (e.g. SDTRIM.SP) in impurity transport code (e.g. GITR)

- Ideal framework to do numerical validations of GITR (e.g. against ERO and DIVIMP) and apply GITR to model impurity transport in Tokamak experiments

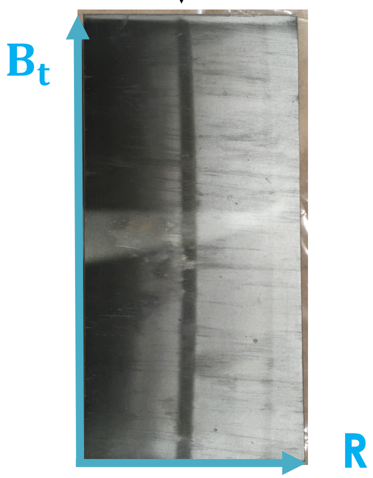
Outline

- Modeling of W ring experiments in DIII-D:
  - C and W erosion/redeposition in DIII-D divertor can be consistently modeled using a Monte-Carlo impurity transport code and sheath & material reduced models:
    - → *Experimental and theoretical framework in DIII-D to validate and use impurity transport code in Tokamak conditions (GITR)*
  - Accurate modeling of C deposition on W may however require a more detailed material model:
    - → *Experimental framework in DIII-D to validate integrated models of surface evolution and roughness, material erosion and impurity transport*
- Modeling W redeposition with ion-gyro sheath:
  - reduced model vs PIC model?
    - → *Example of experimental framework in DIII-D to benchmark PIC simulations with ITER relevant physics*

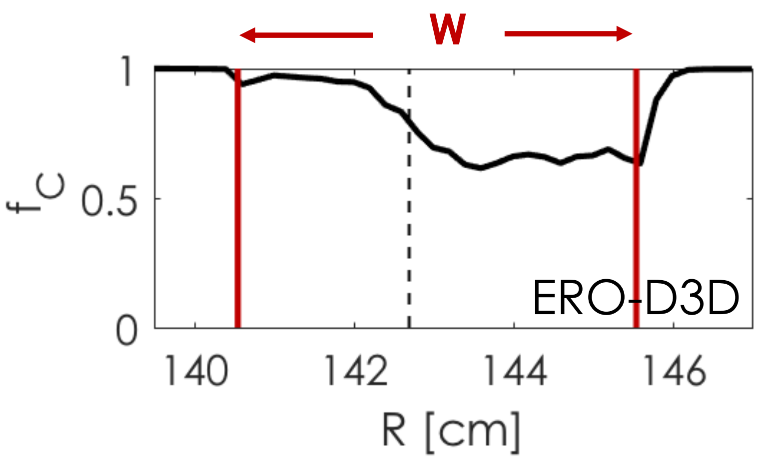
Carbon deposition observed on W at the separatrix location



C deposition strip on W near the strike point



- **Net deposition of C on W ring at the separatrix location**
- Net deposition of C roughly predicted with ERO-D3D in the private flux region but not at the separatrix:



- Homogenous mixed-material model cannot provide accurate modeling of C deposition on W [**DrostePPCF2010**]
- Surface roughness not included in the HMM, but may strongly affect C deposition on W [**KreterPPCF2008**]
- **Modeling of C deposition on W observed during the metal ring campaign in DIII-D might be an good exercise to demonstrate the use of coupled models developed within the PSI-PsiDAC project (here Fractal-TriDyn+GITR)**

Outline

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Large W prompt deposition due to fast ionization of W within the ion-gyro sheath

- **Fast ionization of W ($\tau_{iz}\,\omega_c << 1$):**
  - Large W **prompt** redeposition & W ionization within the sheath

- *Sheath ≈ ion gyro-sheath* at grazing magnetic field incidence [**RyutovCPP1996**] ($\lambda_{sheath} \sim \rho_i$)

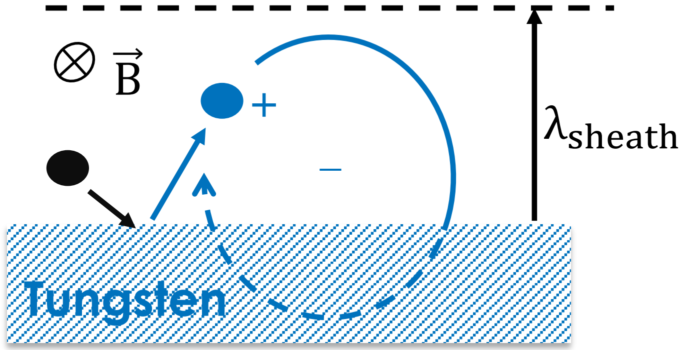
- Recent kinetic simulations [CoulettePPCF2016,StangebyNF2012] show $\lambda_{sheath} \approx 5\rho_i$ … but at B=10T

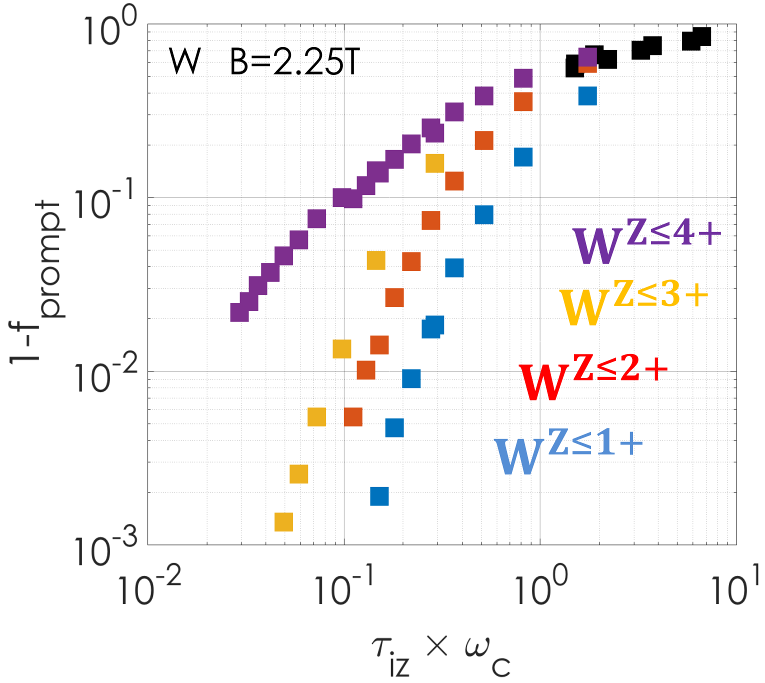
- Large effects of electron density decay in the sheath on W ionization and prompt redeposition (see e.g. [DingNF2016])

$$n_e^{sheath}(\hat{z}) = n_0^{plasma} e^{\hat{\Phi}(\hat{z})}$$

- **W prompt redeposition mainly governed by multiple ionizations of W in sheath**

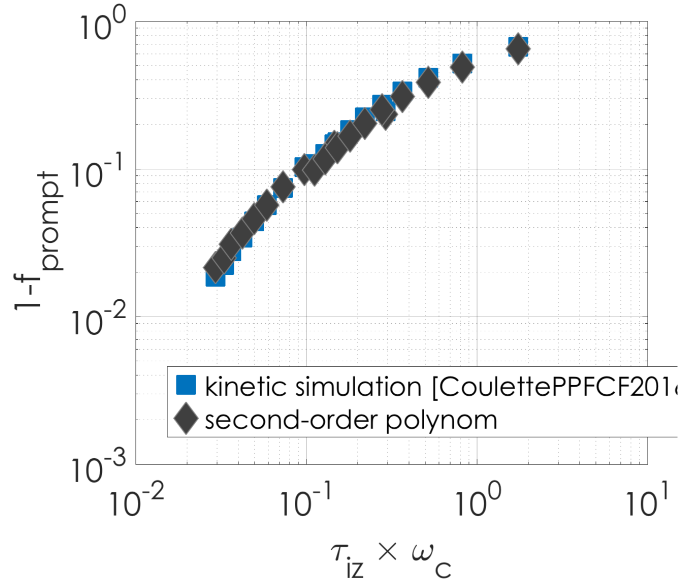
- Critical uncertainties for W prompt redeposition: ionization rates of W. "First-principle" model needed for $W^{0+,1+,2+,3+,4+,5+}$ ionization (see e.g. [**SmythPRA18**])



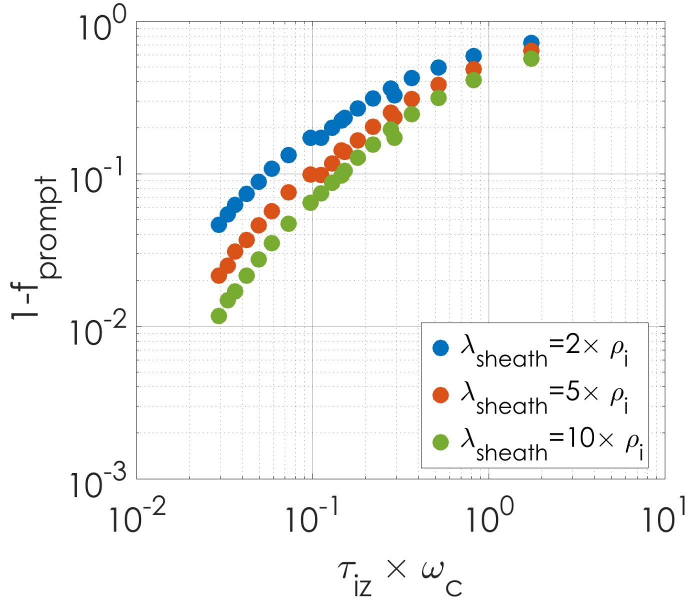


W prompt deposition governed by W ionization rates and sheath scale length and can be described using a sheath reduced model

- **Weak dependency of W prompt deposition on exact potential profile in the sheath**:
  - $f_{iz}(\hat{z}) \sim \int_0^{\hat{v}_c} e^{-\frac{\int_0^{\hat{z}} e^{\hat{\Phi}(\tilde{z})} d\tilde{z}}{\tau_{iz}\,\hat{v}_z}} f(\hat{v}_z) d\hat{v}_z$
  - Allow complete analytical solution for W trajectory in the sheath(convenient for code validation with auto-adjusted timestep in the sheath)



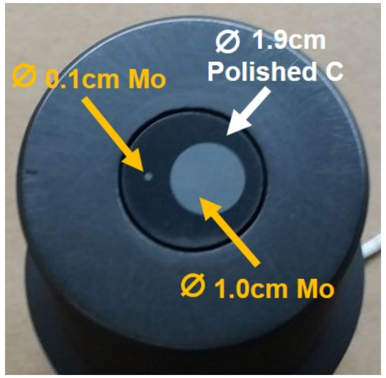
- **Sheath length scale (but not the shape of the potential profile) has non-negligible effects on W prompt redeposition**



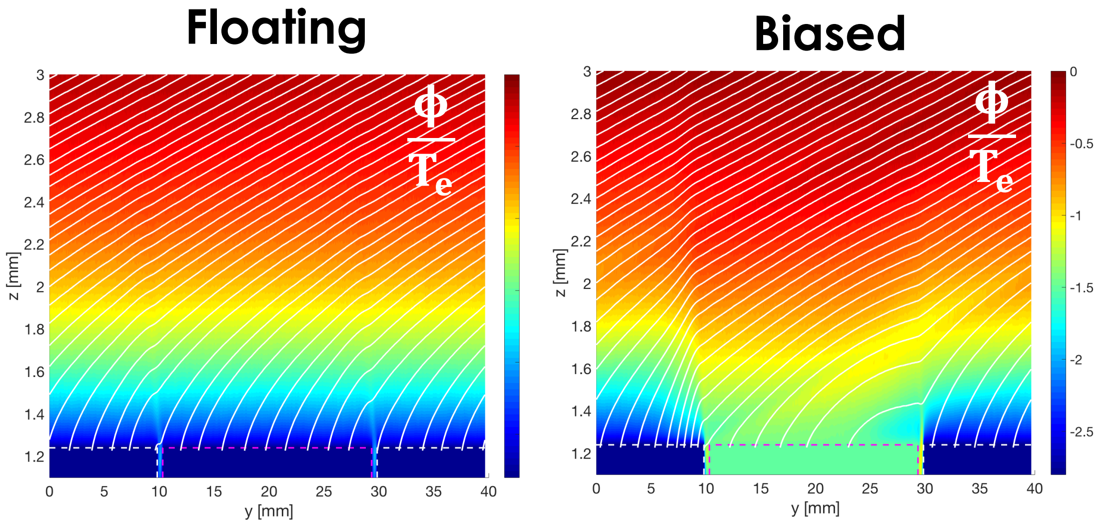
- **Can sheath length scale be well estimated in Tokamak divertor?**
- **If yes, PIC model of the sheath is not always necessary and reduced sheath model might be sufficient, e.g. for simple geometry and steady plasma conditions ($\neq$ ELMs)**

But structure of the sheath may be more complex when considering real PFC geometry, e.g. near W tile edges in ITER W divertor …

- PFC may exhibit complex geometrical features, e.g. W tile castellation and gap in ITER W divertor, which may strongly affect sheath and plasma conditions, and resulting PMI - erosion, melting,…
  - See for example R. Dejarnac talk[1] at PSI



- DiMES biasing experiments performed and modeled by R. Ding[2] at DIII-D exhibit similar geometrical effects on plasma:
  - Modification of the sheath due to gap between biased probe and DiMES head
  - Modification of the sheath due to biasing
  - Modeling of sheath and erosion with PIC and erosion/redeposition codes (here SPICE2/ERO)



- **DiMES biasing experiments in DIII-D may provide an excellent framework to benchmark integrated PIC/impurity simulations in realistic Tokamak conditions with ITER relevant PMI physics**

[1] R. Dejarnac, *Physics of toroidal gap heat loading on castellated plasma-facing components* , PSI 2018
2 R. Ding, *Model validation on DIII-D experiments towards understanding of high-Z material erosion and migration in a mixed materials environment*, PSI 2018

Conclusions

- ***Experimental and theoretical framework in DIII-D to:***
  - *validate and use impurity transport code in Tokamak conditions (GITR)*
  - *to validate integrated models of surface evolution and roughness, material erosion and impurity transport (Fractal-TriDyn+GITR)*
  - *to benchmark PIC simulations with ITER relevant physics (hPIC+GITR)*

- **Well diagnosed and controlled plasma conditions and versality of PFC material in DIII-D divertor provide an ideal benchmark to demonstrate the use of integrated/coupled complex PMI models developed in the PSI-PsiDAC project to analyze and model PMI physics in Tokamak experiments**